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# WATER QUALITY SIMULATION OF TAHOE-TRUCKEE SYSTEM, NEVADA-CALIFORNIA: VOLUME I

Jerome A. Westphal, et al

Nevada University

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A digital inorganic water-quality model was developed for Tahoe-Truckee System Nevada-California. The system consists of mainstem and tributaries of Truckee River between Tahoe City, California and Nixon, Nevada. Flows and inorganic quality of surface waters are influenced by impoundments, diversions for returns from municipal, industrial, and agricultural uses, and ground-water returns.

The Model is based on the principal of mass-flux-balance and presumes 1) that inorganic constituents are conservative, 2) complete mixing occurs instantaneously, and 3) that flows are recapitulated accurately at the defunct gaging station near Truckee, California. The model was developed from 3 years of water-quality data collected monthly at approximately 40 sites along the mainstem and on tributaries. Constituents modeled were bicarbonate, chloride, sulfate, sodium, potassium, calcium, magnesium, silica, and total dissolved solids (minus silica).

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VOLUME I

by

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## ABSTRACT

A digital inorganic water-quality model was developed for Tahoe-Truckee System, Nevada-California. The system consists of mainstem and tributaries of Truckee River between Tahoe City, California and Nixon, Nevada. Flows and inorganic quality of surface waters are influenced by impoundments, diversions for and returns from municipal, industrial, and agricultural uses, and ground-water returns.

The model is based on the principal of mass-flux-balance and presumes 1) that inorganic constituents are conservative, 2) complete mixing occurs instantaneously, and 3) that flows are recapitulated accurately at the defunct gaging station near Truckee, California. The model was developed from 3 years of water-quality data collected monthly at approximately 40 sites along the mainstem and on tributaries. Constituents modeled were bicarbonate, chloride, sulfate, sodium, potassium, calcium, magnesium, silica, and total dissolved solids (minus silica).

The model is designed to simulate concentrations at selected points on the mainstem and in tributaries near confluences with the mainstem. Quality of dispersed flows is also simulated. Dispersed components are treated as point sources. Quality of inputs is predicted as either concentration or flux. Fluxes and flows are added in a downstream direction and concentrations along the mainstem are calculated by dividing flux by flow.



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# SECTION I

## SUMMARY AND CONCLUSIONS

### BACKGROUND

Primary objective of this research was to build a reliable digital simulation model to describe inorganic water quality of surface waters in a complex hydrologic system having both ground- and surface-water components. Secondary objectives were 1) to build the model from a relatively short record of discrete water-quality data and 2) to assess advantages and disadvantages of a mass-flux-balance approach to simulation of inorganic water quality. Tahoe-Truckee system was chosen for modeling because it is representative of many river systems in the western United States with respect to data constraints and types of water use.

Research was done in three phases: 1) predictive equations were developed; 2) model was assembled and operated; and 3) modeling results were evaluated. Phase 1 treated those interrelated hydrologic factors which influence water quality and its prediction. Some fresh insights were gained into established predictive techniques and new predictive techniques were developed to meet demands of the mass-flux-balance concept. Phase 3 resulted in evaluation of strengths and weaknesses of both utility and underlying concepts of the model. Necessary assumptions for the model are: 1) conditions of mass-flux-balance exist; 2) constituents modeled are conservative in nature; and 3) complete mixing occurs between tributary or dispersed inflows and the mainstem. Water-quality indices modeled were bicarbonate ($HCO_3^{-1}$), chloride ($Cl^{-1}$), sulfate ($SO_4^{-2}$), sodium ($Na^{+1}$), potassium ($K^{+1}$), calcium ($Ca^{+2}$), magnesium ($Mg^{+2}$), silica ($SiO_2$), and total dissolved solids (TDS). TDS was calculated as sum of ionic constituents minus $SiO_2$. Hereafter, valence states will be disregarded when referring to ionic constituents.

### PREDICTIVE TECHNIQUES

Predictive techniques for each general type of input (gaged and unregulated, lakes and reservoirs, dispersed) were considered separately.

#### UNREGULATED FLOWS

The most commonly used empirical relationship between chemical concentration and flow is

$$C = aQ^{-b}$$

where

C = concentration ($M/L^3$);
Q = flow rate ($L^3/T$); and
a and b = regression parameters which are often taken to be constant.

For unregulated streams, parameter b appears to be related only to the hydraulic exponent used for computation of critical or uniform flows. In rectangular or trapezoidal channels with uniform flow or flow controlled by a transition from subcritical to supercritical regime, parameter b is constant or very nearly so.

Parameter a depends in part on the hydraulic regime of the stream and in part on the chemical regime. From hydraulic considerations, parameter a is related to parameter b and to slope of the energy grade line. It should remain constant with respect to the hydraulic system as long as uniform flow or a transition from subcritical to supercritical flow prevails. For parameter a to remain constant with respect to the chemical regime, mass of dissolved constituents in the stream reach must remain constant.

If the exponential equation above is fit to data from an unregulated stream, it may be possible to explain deviations from the regression line in terms of changes in parameters a and b. If parameter a is constant with respect to the hydraulic regime and mass of dissolved constituents in the reach increases and decreases in an annual cyclical manner, then deviations from the regression line will be annual cyclical. If mass in the reach is constant but hydraulic controls on flow shift, then deviations from the regression should indicate both an ordinal shift and a change in slope. Under conditions of time-variant mass in the reach and unsteady flow, hydraulic and chemical effects on

parameters a and b are not predictable.

Martis Creek, Sagehen Creek, and Little Truckee River near Hobart Mills were the only unregulated, gaged streams having sufficient data for analysis of predictive equations in terms of the previous discussion. However, only Martis Creek was incorporated into the model. The previously stated exponential predictive equation was best descriptor of flow-concentration relationships in all three streams, except for Cl and $SO_4$. Behavior of Cl and $SO_4$ concentrations was not strongly associated with flow and therefore constituted a problem which was treated separately.

Deviations from regression lines were random except at Martis Creek. Logarithmic plots of concentrations versus flows appear to have a flatter slope (b) and a lower ordinate intercept (a) during base flow months than those which would govern during periods of higher flow. This may be indicative of a shift on hydraulic controls between low and high conditions of flow. Deviations from regression lines were annual cyclical and probably reflect annual cyclical changes in influx of dissolved constituents associated with snowmelt runoff and flow of some perennial springs in the basin.

Cl and $SO_4$ concentrations are not strongly associated with variations in flow in the three streams. Except for Cl in Martis Creek, concentrations of these constituents in snow, snowmelt, and streamflow appear to be precipitation derived. As such, they would not vary markedly with flow. In Martis Creek, Cl concentrations range from 0.82 to 12.65 mg/l. Cl concentrations in springs in the drainage range from 0.5 to 9.0 mg/l. Although geologic materials appear to be one source, at least part of the variation in Cl concentrations can be attributed to road salting along California Highway 267.

## REGULATED FLOWS

Flow and flux routing through impoundments precludes an exponential relationship between concentrations and release rates. In Tahoe-Truckee system, releases from Lake Tahoe, Donner Lake, and Prosser and Boca Reservoirs are regulated by control structures. Operation of Stampede Reservoir resulted in changed operation policy at Boca Reservoir downstream and subsequently, a change in chemical regimen in that reservoir. A dam was also constructed on Martis Creek during late spring 1971 for purposes of flood control. Chemical regime of Martis Creek remained unchanged and may remain so except during periods of active impoundment in the reservoir.

Chemical quality of releases from Boca and Prosser Reservoirs appears to be associated with reservoir operating procedures. Although mixing processes are unknown they are undoubtedly influenced by reservoir geometry which is governed in turn by operating policy. Under assumption of complete mixing, concentrations are also related to reservoir storage, inflow, and inflow concentrations. Because reservoirs act as routing devices, concentrations in releases reflect lagged (with respect to time) responses to annual cyclical variation of inflow concentrations.

Multiple regression equations were used to relate concentrations in releases to predictor variables which best reflect appropriately lagged inflow concentrations and mixing processes within the reservoirs. Because of the change in chemical regime associated with operation of Stampede Reservoir, two sets of equations were required for Boca Reservoir. The same predictor variables were used for each constituent within a set of equations.

At Boca Reservoir, concentrations of all constituents were anomalously high when release rates dropped below 0.5 cubic feet per second (cfs). This is probably due to seepage through the dam. Therefore, whenever flow rates are less than 0.5 cfs, simulated concentrations are set equal to average concentration observed for those rates.

Concentrations in releases from Lake Tahoe do not vary with release rates, lake elevation, nor elevation changes. Although fluctuations are small, annual cyclical behavior is discernible for $HCO_3$, $SO_4$, Na, K, and TDS. Runoff rates in the vicinity of Lake Tahoe are also annual cyclical. Therefore, it is likely that concentrations in outflows reflect influx of dissolved constituents in locally derived runoff and subsequent dilution in the lake near the outlet.

Because behavior of sulfates is inverse to that for $HCO_3$, Na, K, and TDS, actual seasonal variation is unlikely. Random behavior of Ca, Mg, and $SiO_2$ concentrations cannot be satisfactorily explained at this time. For $SO_4$ and constituents exhibiting random behavior, predicted concentrations in outflows were taken to be the average of all observations. For constituents having annual cyclical behavior, predicted concentrations were taken as the average observed for the month of interest.

Chemical quality of flows in Donner Creek near its confluence with Truckee River reflects quality of 1) releases from Donner Lake; 2) unregualted flows in Cold Creek; and 3) dispersed flows downstream from Donner Lake and Cold Creek. Inadequacy of storage records at Donner Lake precludes evaluation of effects of inflow, storage, or reservoir geometry on chemical quality of releases. Fortunately, concentrations in releases are nearly constant except for anomalously high values at flow rates less than 1.5 cfs. High values are caused by dispersed flow

between Donner Lake and the gaging station. Predicted concentrations in releases from Donner Lake are taken to be the average of all observations except when flow rates are less than 1.5 cfs. Then average anomalous value is assumed. Exponential flow-concentration equations are used to predict chemical quality of Cold Creek flows.

Use of sums of fluxes and flows from Donner Lake and Cold Creek to predict concentrations in Donner Creek near its confluence with Truckee River results in consistent underestimation. The disparity is attributed to input from dispersed sources. For prediction, concentrations calculated from the flux-budget methods are adjusted upward by the mean difference between simulated and observed for the period July 1968 through March 1971.

## DISPERSED FLOWS

To develop dispersed flow-concentration/flux relationships, Truckee River was divided into six reaches bounded by gaging stations. Dispersed flows and fluxes were taken as differences between output from and input to a reach. Under certain restrictive assumptions, chemical quality of dispersed flows can be described by flow-concentration relationships which are exponential in form. This can occur when a reach constantly gains throughout its length and 1) input is from unregulated tributaries; or 2) input is ground water from bank storage or contiguous aquifers recharged by over-bank flooding.

Although dispersed fluxes in Tahoe-Truckee reach are calculated by difference, dispersed flows are generated by a hydrologic model (Butcher, et al., 1970). By definition negative gains are precluded in this reach. This appears to be consistent with the physical situation. However, calculations of dispersed fluxes and concentrations often result in negative values. This is primarily due to insufficiencies of the flow model. If negative values are disregarded, dispersed flow-concentration relations are exponential in form. Regression coefficients are very near or within the range of values calculated for five tributaries to the reach. Ordinate intercepts are higher than those observed for individual streams because dissolved constituents are more concentrated in unsampled components of dispersed flow.

Calculation of dispersed fluxes and flows in Truckee-Farad reach often results in negative values. Hydrologic evidence contradicts this possibility. In most instances inconsistencies can be attributed to a combination of gaging errors and errors in estimation of Donner Creek and dispersed flows along Tahoe-Truckee reach. In terms of overall model reliability, dispersed quality in this reach can best be described by exponential flow-concentration relations. When losses are indicated, concentrations at Farad are calculated from sum of fluxes and flows from gaged sources along the reach. Flow-concentration relationships are less well defined than in other reaches. Regression parameters do not correspond with those calculated for individual tributaries along the reach because of dissimilarities in physiographic features among tributary basins along the reach and presence of a significant ground-water component.

Although Truckee Meadows reach has the most complex hydrology, it is similar to Vista-Derby Dam and Derby Dam-Wadsworth reaches in terms of prediction of dispersed quality. Relationships between river and contiguous aquifers are not well defined. Records of surface-water diversions and returns are incomplete. Ground- and surface-water exchanges may take place simultaneously. Net flow losses occur in all three reaches and net flux losses also occur except in Truckee meadows reach. Net flux/net flow relationships provide best basis for prediction of dispersed quality in these reaches. Records show net flows larger than those observed during this research. Therefore, to simplify extrapolation procedures in the model, flux/flow pairs were estimated at extremes and a fourth order polynomial was fit to each "extended" data set for use in calculations.

In Wadsworth-Nixon reach, there are diversions for agriculture adjacent to the river. Accretions to the reach are due primarily to ground water. When losses occur they are usually associated with high flows. In terms of recapitulation of concentration Nixon, exponential dispersed flow-concentration relations were superior to net flux/net flow relationships. F periods of net flow loss, concentrations at Nixon were set equal to those at Wadsworth.

## STOCHASTIC COMPONENT

To complete simulation, it is necessary to account for unexplained variance in each predictive equation. This was done by adding to each predictive relationship the product of standard deviation of differences between estimated and observed concentrations (residuals) and a random number from a population of zero mean and unit variance. In most cases residuals were approximately normally distributed about a zero mean. In cases where this was not true, the central limit theorem was assumed to apply.

## MODEL STRUCTURE AND VERIFICATION

Model structure is uncomplicated. Main program is used to input data and parameters for predictive equations and to output results of calculations. Subprograms are used to simulate concentrations. For each reach, flux and/or concentration is calculated for each input source. Fluxes are then added and concentrations calculated for the downstream end of the reach. Calculations proceed in a downstream direction so that flow and quality conditions at the end of one reach are specified as input to the next. All operations are performed for one constituent at a time for the desired length of record.

Model verification procedures were categorized as internal and external. The former relates to data developed in the course of this research and the latter to data collected at Floriston by the United States Geological Survey (U.S.G.S.) during water years 1965 through 1969. Although subjective criteria are entirely valid and were applied, discussion of model verification centers primarily around statistical measures. Intensity of association between simulated (recapitulated) and observed concentrations can be inferred from correlation coefficients. Tendency to under- or over-estimate (negative or positive bias) is tested according to procedures for paired data using Student's t as criterion under the null hypothesis that mean differences are not different from zero. The five percent level of significance was selected for acceptance or rejection of the null hypothesis.

In keeping with research objectives, data used for formulation of predictive relationships were limited to 36 months or less during the period December 1967 through March 1971. Data collected between March 1971 and March 1972 were used only for internal verification. Concentrations were recapitulated on the mainstem at Tahoe City, Truckee, and Farad without bias, except for Cl and $SO_4$ at Farad. However, magnitudes of biases are near or within limits of analytical error for very dilute waters. Intensity of association between simulated and observed concentrations is negligible at Tahoe City due to small variances of populations of concentrations. At Truckee and Farad, correlation coeffecients range from 0.18 to 0.71 with little difference between stations.

Simulated concentrations at Reno reflect uncertainties in Farad simulation as well as uncertainties in Reno-Farad predictive equations. Values of correlation coefficients decrease slightly. Bias in simulation of Cl and Ca concentrations exists but amounts to less than 0.35 mg/l for either constituent.

Although correlation coefficients at Vista range from 0.64 to 0.90 and represent a significant improvement from Farad and Reno, significant bias is induced in simulations of $HCO_3$, Na, K, Ca, $SiO_2$, and TDS. In all cases the model over estimates. Indications are that bias is due to a change in quality regime of Truckee Meadows during the period April 1971 through March 1972. Bias was transmitted nearly intact downstream to Derby Dam. Correlation coefficients also remained essentially unchanged.

Because of peculiarities in plotting positions of data for dispersed flux-flow relationships in Derby Dam-Wadsworth reach, extrapolation procedures resulted in negative bias in predictive equations for all constituents except Mg and $SiO_2$. Although apparent bias at Wadsworth appears only for simulation of $SO_4$ and $SiO_2$ concentrations, the improvement is a result of compensating error and not improved predictive capability. Correlation coefficients remain about the same as for Vista and Derby Dam.

Negative bias at Nixon is caused in part by underestimates at Wadsworth and by the simulation process in Wadsworth-Nixon reach. When flow losses occur, concentrations at Nixon are set equal to those simulated at Wadsworth. Although concentrations of dissolved constitutents in flows appear to become more concentrated during periods of net loss, data are insufficient to make a conclusive argument to that effect. Except in the case of $SiO_2$, correlation coefficients range from 0.90 to 0.98 indicating most intensive degree of association between simulated and observed concentrations in the system.

To check internal consistency, sum of average simulated concentrations was compared to simulated TDS at each station. Percent error in terms of TDS ranged from -2.4 percent to 3.4 percent, largest error occurring at Reno. Therefore, with possible exception of simulation at Reno, the model appears to be internally consistent with respect to generated data.

Concentrations were simulated for external verification on the basis of mean monthly flow conditions. Simulated concentrations (except $SiO_2$) at Farad were compared to U.S.G.S. data at Floriston 2.5 miles upstream. Data from water years 1965 through 1969 were used for comparisons. Correlations were generally better than for internal verification at Farad. However, estimates of Cl, Ca, Mg, and TDS concentrations were biased. For the latter three constituents, bias apparently arises from a tendency for the model to underestimate high extremes. This may be because the data base for the model does not reflect drought conditions. Bias in estimates of Cl concentrations is in the opposite direction and may be indicative of relatively recent changes in road salting practices.

The concept of mass-flux-balance could also be applied if flow-concentration relations were formulated for

points on the mainstem. For purposes of comparison, exponential flow-concentration equations were developed for Truckee River near Farad using U.S.G.S. data. Except for $SO_4$ concentrations, flux budgeting resulted in a higher degree of association between simulated and observed constituents than did the flow-concentration method.

Cl , $SO_4$, and TDS concentrations simulated for the period October 1963 through March 1972 were subjected to frequency analysis. For comparison, U.S.G.S. data at Floriston were also subjected to frequency analysis. Theoretical distributions for TDS are consistent for the two data sets (both are normal distributions) but simulated values which would be equalled or exceeded 2 percent of the time are about 7.5 mg/l less than commensurate observed data. Because there are 102 simulated concentrations as opposed to 60 observed, it is clear that the model tends to underestimate extremes for TDS concentrations.

Although theoretical distributions for Cl concentrations are not identical, for practical purposes they are the same when the probability for being equalled or exceeded decreases below 30 percent. Theoretical distributions of $SO_4$ concentrations are totally different for the two data sets. Differences can be traced to uncertainties in prediction of $SO_4$ concentrations in Tahoe-Truckee reach. Effects are identifiable as far downstream as Reno gage.

At other points on the mainstem, simulated concentrations tended to be according to Gringorten's curves 1, 2, or 3. Exceptions were at Nixon where distributions are fit by Gringorten's curve 5, Wadsworth where $SO_4$ concentrations follow Gumbel's double exponential distribution, and at Truckee where Gringorten's curve 6 best describes distribution of Cl concentrations.

## SUMMARY

It appears that a model having reasonable predictive capability can be built from a data record of about 36 months. The discrete (with respect to time) nature of data is not a particularly formidable obstacle in Tahoe-Truckee system. Principal difficulties lie with development of well defined predictive relationships. Shortcomings of empirical relationships are well known. If cause and effect is implied, it may be possible to assess reliability of an equation in terms of stability of specific related factors within the system. Otherwise, extrapolations are tenuous.

An attractive feature of the mass-flux-balance concept is that stresses are transmitted downstream in the model in a manner similar to that observed in real systems. Decomposition of the system into individual sources of flux and flow results in more detailed understanding of factors influencing the quality regimen than would be achieved if development of predictive equations were limited to sites on the mainstem. However, increasing the number of predictive equations can result in biased estimates. This disadvantage appears to be offset by increased capability to simulate behavior patterns.

Analyses show that Tahoe-Truckee model simulates concentrations of conservative constituents with sufficient accuracy to be useful as an analytical tool. Although bias is present in simulation of certain constituents at gaging sites below Farad, it is comparatively small and, except at Vista and Reno, was incorporated into the simulation as a compromise to reduce programming complexities.

It appears feasible, given the flow data, to extrapolate the water-quality regime of an entire system either forward or backward in time. A synthetic water-quality record based on historical flows is a means for overcoming inadequacies of limited data as they relate to the historical quality. In a similar manner, forward projection of the water-quality record on the basis of stochastic flow generation and hypothetical system stresses has powerful management implications with regard to human activity as it relates to quality of the water resource.

## SECTION II

## RECOMMENDATIONS

An important facet of this research was applicability of predictive techniques developed herein to other comparable river systems. With regard to this aspect, research results amplify the importance of three assumptions basic to developemnt of the simulation model. First, the assumption of conservative behavior of inorganic constituents appeared to be valid for Tahoe-Truckee system. However, in systems with waters having higher concentrations and/or differing mixes of dissolved constituents this assumption may not hold. Prior to attempting a model of the type developed in this research, criteria should be established for determining whether or not ionic constituents have conservative behavior.

Second, the assumption of complete mixing implies that water quality in a cross section can be determined from analysis of a grab sample. Additional research is required to establish criteria for selection of sample sites, to determine if complete mixing occurs in a stream cross section, and if not, to develop methods for relating average quality in cross sections to that determined from grab samples.

Third, the constraint of a short, intensive data record makes it unlikely that flow extremes will be encountered. This raises the possibility that predictive equations will not accurately reflect extremal quality conditions. Therefore, more research is needed to test underlying hypotheses of various types of predictive equations and to establish probable ranges of their validity.

In Tahoe-Truckee system, Cl and $SO_4$ were the constituents most difficult to model. In low concentrations (less than 1.0 mg/l Cl and 3.0 mg/l $SO_4$), they appeared to be principally precipitation derived. In greater concentrations, Cl was often diagnostic of road salting and both may have been associated with domestic and agricultural wastes. To increase accuracy of simulation it is necessary to understand more about the variation of these constituents with precipitation and to develop methods of tagging and relating these constituents to specific types of human activity.

For some reaches prediction of dispersed quality was based on polynomial fits to flux-flow data. This method should be tested more thoroughly to determine if it is justifiable on theoretical grounds and to determine limits of its reliability. The method of extropolation beyond recorded extremes of flux also needs to be examined critically.

The flux-budgeting method appears to be superior to the on-site flow-concentration method for simulation of most inorganic, conservative constituents in relatively dilute waters. To increase the versatility of this model, additional research should be conducted to develop methods for adapting nonconservative constituents to the flux-budgeting concept.

# SECTION III

# INTRODUCTION

## BACKGROUND

In recent years hydrologic research has focused on development and application of simulation techniques. The simulation concept has been applied to both flow and quality aspects of ground- and surface-water systems. The fundamental objective is to be able to predict hydrologic or quality responses under imposed stress conditions. Anticipation of consequences of alternative courses of action offers possibility of improved utilization of a water resource.

Simulation is achieved through use of models. These may be iconic (look-alike), analog, or digital; the latter two being most prevalent. Models can have many levels of sophistication depending on available data and desired accuracy for the simulation. Usually, higher levels of accuracy require a relatively detailed understanding of the physical processes at work in the system being modeled.

Effective management of many river systems in the United States requires an understanding of the existing water-quality regime. Characteristics common to a number of these systems constrain simulation to a limited number of water-quality indices and/or limit it to a small part of the system of interest. Water-quality data are usually discrete with respect to time and limited with respect to length of record, density of data collection sites, and water-quality indices measured. Although flow data may be adequate for description of system hydrology, flows in small tributaries, irrigation returns, water discharges, and accretions/depletions of ground water are seldom measured individually. These unmeasured components can have a profound effect on water quality.

## PURPOSE AND SCOPE

Principal objective of this research was to develop a digital simulation model to describe inorganic quality of surface waters in a complex hydrologic system having both ground- and surface-water components. Secondary objectives were: 1) to build a reliable model based on a relatively short record of discrete data, and 2) to assess advantages and disadvantages of a mass-flux-balance approach to simulation of inorganic water quality.

The Tahoe-Truckee system (Figure 1) was chosen for modeling. This system is representative of many river systems in the western United States with respect to data constraints and types of water use. Records of inorganic water quality are limited to those developed in the course of this research plus approximately eight years of monthly records for Truckee River near Floriston, California. Continuous flow records exist for periods of about 7 to 60 years at 8 sites on the river plus 4 sites on major tributaries.

Truckee River flows from Lake Tahoe north and east within the Carson Range of the Sierra Nevada to Farad, California. Snowmelt runoff in this part of the basin is the ultimate source of most of the flow. Flows in this reach are regulated principally by outlet structures at Lake Tahoe and Donner Lake, Prosser Reservoir on Prosser Creek, and Boca and Stampede Reservoirs on Little Truckee River. Water is used primarily for domestic and municipal purposes along the river above Farad.

From Farad, Truckee River continues eastward out of the mountains across Truckee Meadows to Vista, Nevada. Truckee Meadows is site of Reno-Sparks urban area as well as considerable agricultural development. Most water diverted from Truckee River and flows from streams in adjacent mountains are utilized in the meadows and are returned to the river (less consumptive use) via Steamboat Creek and North Truckee Drain. In addition, Steamboat Creek carries highly mineralized waters from Steamboat Hot Springs and treated municipal effluent from the Reno-Sparks plant to the river. At present, flows from Steamboat Creek and North Truckee Drain are the principal degrading influence on inorganic quality of Truckee River.

From Vista, Truckee River flows eastward through Truckee Canyon to Derby Dam where, during irrigation season, part of the flow is diverted out of the basin to Truckee-Carson Irrigation District lands near Fallon, Nevada. The river flows out of Truckee Canyon at Wadsworth, Nevada, then north past Nixon, Nevada, to Pyramid Lake. Agricultural returns and inflow from regional ground-water systems further degrade quality along this reach.

The model was developed on the premises that 1) inorganic water-quality parameters obey mass balance relations, 2) an operational hydrologic model existed (Butcher, et al., 1970) which could be used to recapitulate Truckee River flows at the defunct gaging station near Truckee, California, and 3) the hydrologic model would ultimately be modified to reflect all existing stream gaging sites on the mainstem and major tributaries. Development

of a water-quality model commensurate with the existing hydrologic model would necessitate abandoning the mass-flux balance concept in reaches below Vista and would require that Martis Creek be incorporated into the dispersed component between Truckee and Farad. Therefore, the water-quality model was based on historic flows with realization that full potential for stochastic generation of inorganic water-quality parameters would not be achieved with the existing hydrologic model.

Lack of historical water-quality data was the primary constraint on development of a model. Analyses of water samples collected monthly for approximately three years provided data necessary for predictive equations. Effects of regulation on river flow with regard to both impoundments in the upper reach and diversions in the lower reach complicated efforts to develop predictive equations. Research was oriented toward development of empirical predictive techniques which would be applicable to other systems.

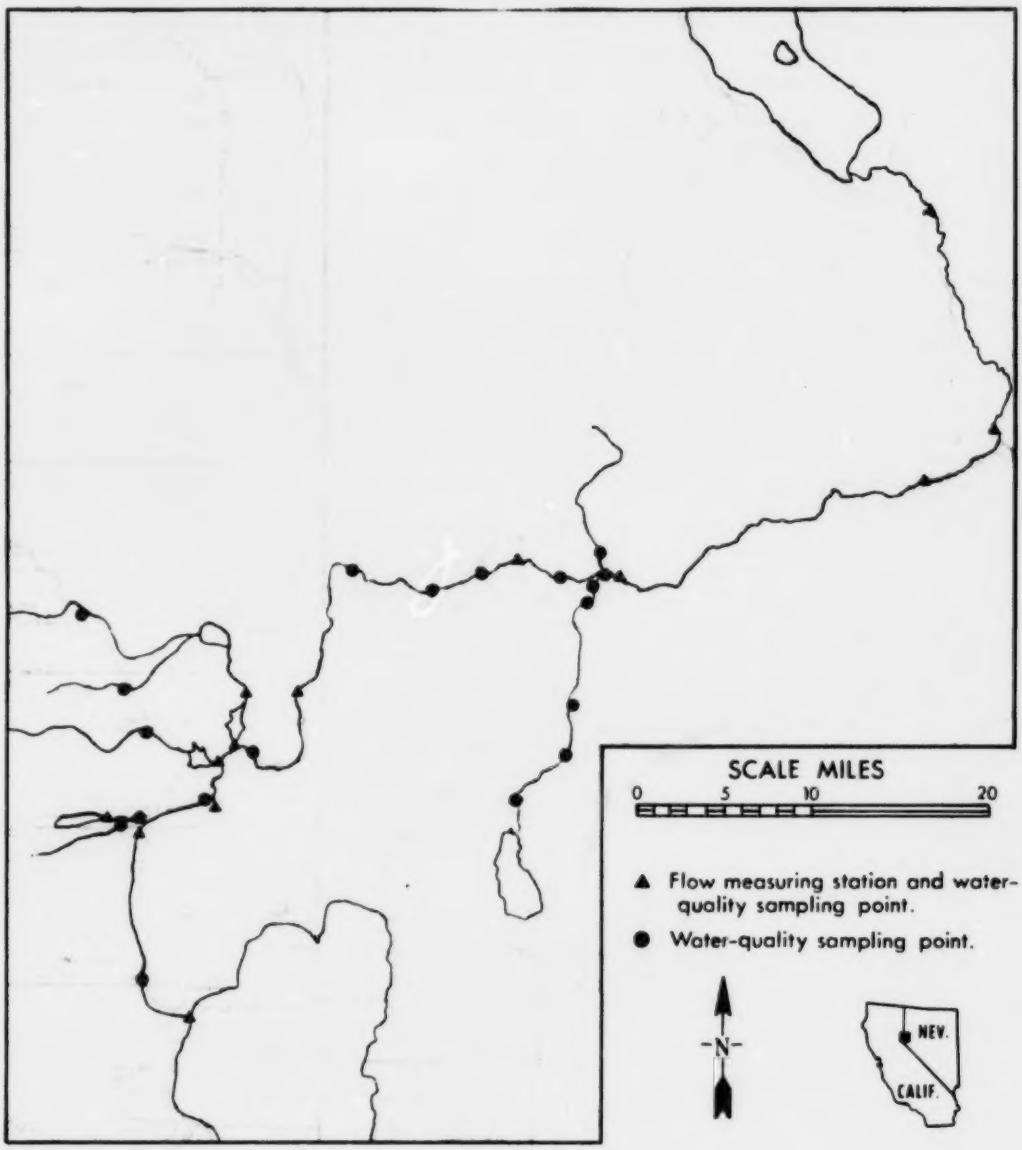


**FIGURE 1. Map of Tahoe-Truckee System Showing Location of Selected Flow-Measuring Stations and Water-Quality Sampling Points.**

## SECTION IV

## SIMULATION MODEL

### CONCEPTUAL MODEL

The model is designed to simulate concentrations of inorganic water-quality parameters at selected points on the mainstem and in tributaries near their confluences with the mainstem. Water-quality parameters simulated by this model are conservative in nature, changes in dissolved load being associated only with accretions or depletions in flow along any given reach. Conditions of mass balance are presumed to hold such that simulated quality is representative of the system at a particular instant in time.

The model is composed of two basic components: 1) a set of predictive equations, and 2) a suite of flow records for gaging stations on the mainstem and tributaries. Flow records may be based either on historical flows or on synthetic flows generated through operation of a hydrologic model. Flows are used either explicitly or implicitly (in the case of impoundments) as predictor variables for water quality. Because flows are also the transport medium for quality parameters, accurate and relatively detailed water budgeting is a prerequisite for successful model operation.

Predictive equations fall into two categories, 1) those used to estimate concentrations, and 2) those used to estimate mass flux. The former are used where there are no losses of water in a given reach, and where losses may occasionally occur but have no significant effect on concentrations in the river. The latter are used in reaches where exchanges between the river and contiguous surface- and ground-water systems have a measurable effect on both flow and concentrations.

Conceptually, the model is uncomplicated. For measured tributary inflows and reaches where net losses from the river have minimal effect on downstream concentrations, input concentrations are estimated. Input fluxes are then taken as the product of inflow and concentration,

$$F = C \times Q \qquad (1)$$

where

F = mass flux ($M/T$),
C = concentration ($M/L^3$), and
Q = flow rate ($L^3/T$).

In reaches where exchange between river and ground water and/or surface waters has a measurable influence on both flow and quality net fluxes are estimated directly. Flux in the mainstem is then calculated by summing fluxes in a downstream direction. For any given reach of the mainstem, flux at the downstream end is equal to flux at the upstream end plus input fluxes (and/or minus outfluxes) in the reach,

$$F_D = F_U + \Sigma F_I$$

where subscripts D, U, and I refer to downstream, upstream, and input (or output), respectively. Assuming complete mixing, concentration at the downstream end of the reach is calculated by dividing flux by flow at that point,

$$C_D = \frac{F_D}{Q_D} + \frac{F_U + \Sigma F_I}{Q_U + \Sigma Q_I} \quad .$$

### DATA INPUT

Two basic types of data were needed to develop the model, 1) water-quality data, and 2) hydrologic data. Because water-quality data were severely limited (eight years of monthly records near Floriston, California), it was necessary to establish a water-quality monitoring network. The network was designed with the objective of providing data for establishment of predictive equations and for verification of the model.

Along the mainstem, sample collection points were established below major tributaries and near gaging stations. Additional sites were selected in Truckee Meadows reach for the purpose of monitoring urban effects on

water quality. Sampling sites were also selected on major tributaries near gaging stations and above reservoirs and on minor tributaries near their confluences with the river. In all cases, sites were located such that it was probable that flows in the cross sections were completely mixed.

The monitoring network consisted of approximately 40 points from which water samples were collected monthly for analysis. At eight additional sites, primarily minor tributaries, samples were collected bimonthly. The entire network was sampled on the same day (about the first of the month) to minimize effects of changing flow on quality and to provide an "instantaneous" description of quality and flux of water-quality parameters throughout the system. A grab-sampling technique was employed because time required for sampling and inaccessibility of stream cross sections over full range of flows made compositing techniques infeasible.

Standard analyses included pH, electrical conductivity, $HCO_3$, carbonate ($CO_3$), Cl, $SO_4$, Na, K, Ca, Mg, and $SiO_2$. TDS was calculated as the sum of dissolved constituents less $SiO_2$. Individual ionic constituents and TDS were modeled. Carbonate species in Truckee River and its tributaries are primarily $HCO_3$. Therefore, $CO_3$ was not modeled.

Hydrologic data included daily and monthly flows at river and tributary gaging stations and reservoir storage records. Published and preliminary streamflow records were obtained from the United States Geological Survey, Water Resources Division, Carson City, Nevada. During this research, annual flows ranged from about 78 percent to 200 percent of the average as measured at Farad. Storage records from Lake Tahoe, Donner Lake, and Boca and Prosser Reservoirs were provided by Sierra Pacific Power Company. Storage records for Stampede Reservoir were provided by the Bureau of Reclamation, Carson City, Nevada.

To establish predictive equations for inorganic quality of reservoir outflows and to develop reconstituted flows at the now defunct gaging station at Truckee River near Truckee, California, it was necessary to estimate historical unregulated flows in Prosser Creek and Little Truckee River. Climatological data from monthly summaries of the United States Weather Bureau were used for this purpose. A hydrologic model (Butcher, et al., 1970) was used to reconstitute inflows above the old Truckee River gage near Truckee.

## PREDICTIVE TECHNIQUES

As stated earlier, the purpose of simulation models has been to predict response of a system to a given set of external conditions. In this case, the problem was to take a limited number of noncontinuously measured (discrete with respect to time) water-quality data and to develop a reliable method for simulating conservative inorganic parameters along Truckee River between Tahoe City, California and Nixon, Nevada. In systems where waters are saturated with respect to one or more constituents, conservative bahavior would be an invalid concept. However, in Tahoe-Truckee system, where water in tributaries and mainstem are relatively dilute and chemically similar, there is no evidence of nonconservative behavior of constituents.

A deterministic approach to modeling was precluded by a lack of quantitative information pretaining to those factors which control inorganic water quality in hydrologic systems. However, it has long been known (Lenz and Sawyer, 1944) that inorganic water quality can vary with flow rate. Sharp (1969, 1970) discussed time variant characteristics of water quality in hydrologic systems. From these fundamental ideas, it has been possible to develop empirical equations for estimation of water-quality parameters.

Empirical relationships seldom connote cause and effect. Their validity lies only within the range and period of historical observations. Use of these relationships to project beyond the range or period of observations is always suspect. However, empirical methods are often the only rational means of extrapolating beyond the record. Recognition of causative factors and their probable direction of influence helps justify an extrapolation and is useful for estimation of the range of its validity.

### UNREGULATED FLOWS

The most commonly used empirical relationship between chemical concentration and flow is expressed as

$$C = aQ^{-b} \qquad (2)$$

where

$C$ = concentration ($M/L^3$)
$Q$ = flow rate ($L^3/T$), and
$a$ and $b$ = regression parameters.

Ledbetter and Gloyna (1964) tested Equation (2) on rivers in Oklahoma and Texas. They found that the line slope, b, was not constant but varied with antecedent flow conditions. Gunnerson (1967) found that certain constituents in waters of the Snake River exhibited a cyclical effect when plotted as concentration versus flow on log-log paper. Hendrickson and Krieger (1964) also observed cyclic progressions of the flow-concentration relation in Salt River, Kentucky.

Assuming complete mixing of conservative parameters in an arbitrary mixing volume, the expression for mass at any given time is

$$M = CV \tag{3}$$

where

M = mass of dissolved constituent (M),
C = concentration of dissolved constituent ($M/L^3$), and
V = arbitrary mixing volume ($L^3$).

Stage-discharge curves are often used to describe the relationship between depths of flow and flow rates in natural streams. The curves are derived empirically from gaged flows and commensurate observations of stream stage. For uniform flow in channels which are wide or have shallow depths of flow with 1) rectangular cross sections, 2) energy grade lines of constant slope, and 3) invariant channel roughness, Manning's equation shows that flow rate can be closely approximated by the product of a constant and the 5/3 power of flow depth. Therefore, under prevailing assumptions outflow may be related to storage (V) in a reach according to the expression

$$Q_o = KV^n \tag{4}$$

where

$Q_o$ = outflow ($L^3/T$),
K = proportionality constant, and
n = empirical exponent.

Rearranging Equation (4) yields

$$V = K^{-1/n} Q_o^{1/n} \quad . \tag{5}$$

Substituting for mixing volume in Equation (3) and rearranging terms yields an expression for concentration

$$C = MK^{1/n} Q_o^{-1/n} \quad . \tag{6}$$

By defining parameters "b" and "a" as

$b = 1/n$ and
$a = MK^b$,

Equation (6) becomes

$$C = aQ_o^{-b} \tag{7}$$

exactly as expressed in Equation (2). Thus, justification for the exponential relationship is clear. However, violations of implicit assumptions may cause deviations from predicted behavior. To assess the limitations of Equations (2) and (7) it is necessary to understand which factors influence the parameters of Equation (6).

Under the prevailing assumption of uniform flow, parameters n and K are analogous to stage-discharge parameters. For rectangular or trapezoidal channels, n increases linearly with the hydraulic exponent discussed by Chow (1959, pp. 66 and 131) and at a lesser rate. Its value is dependent on shape of the cross section and ratio of flow depth to bottom width. For trapezoidal cross sections with side slopes steeper than 30 degrees and for rectangular cross sections, the hydraulic exponent (hence n) changes less than 5 percent after width to depth ratios

increase beyond 10:1. For width to depth ratios greater than 20:1 the hydraulic exponent is essentially constant. Factors relating to values of K are not well defined. However, from Chow's discussion of conveyance it relates to slope of the energy grade line and should be constant valued for all flows.

Stage-discharge curves are often developed for reaches in which flows are controlled by natural or man-made structures which force flows to transition from a subcritical to supercritical regime. Because the transition through critical depth requires a unique stage-discharge relationship, the assumption of uniform flow is not necessary. If the control (critical flow) cross section is rectangular, the hydraulic exponent is constant for all depths. For trapezoidal sections the variation is similar to that discussed previously. Although the stage-discharge relationship is exponential in form (or approximately so) at the control section, this feature will be preserved at a section upstream only when stage in that section is related exponentially to stage in the critical section. Broad crested weirs in rectangular channels and Parshall flumes are devices which cause exponential stage-discharge relationships.

In the absence of a critical flow control section or conditions of uniform flow, parameters n and K are less well defined. With unsteady flow, depths will not correspond to a unique discharge rate. In some streams unsteady flow results in different stage-discharge curves for rising and falling limbs of a hydrograph. Unsteady flow may also result in a rating curve which is not well defined but is best described by an exponential equation.

As defined earlier, parameter a of Equations (2) and (7) consists of 3 components. Parameters K and n have been shown to be hydraulic components whose variation will cause parameter a to vary. The other component is mass (M) in the mixing volume (stream reach). Analyses of water samples taken from wells and springs show that concentrations of dissolved constituents in ground water often change with respect to time. Direct runoff and interflow contain dissolved constituents whose concentrations may vary with time. Therefore, any reach receiving contributions from these sources is subject to having its dissolved mass change with respect to time.

For any given reach, factors controlling volume-discharge relationships are relatively fixed unless altered by effects of human activity. If shifting control sections or unsteady flow cause hydraulic parameters to change such that the observed concentration is different from the predicted, then conditions which produced the deviation will cause the same behavior each time they occur. Effects of time variation of mass are independent of hydraulic effects. Direct runoff, interflow, and ground water entering a reach will cause parameter a to increase if all other factors are constant. The result will be an observed concentration greater than predicted. When mass contributed by base flow decreases and other factors are constant, then actual streamflow concentrations will be less than expected. However, because hydraulic factors and time variation of mass act independently, their individual effects may either cancel or be additive.

Although amplitudes of flows may vary from year to year, it is likely that over an annual period a stream reach will always experience conditions ranging from direct runoff and interflow to base flow. In reaches where the volume-discharge relationship is subject to shifting controls or unsteady flow, the range of flows and flow conditions in any year is probably sufficient to produce these hydraulic effects. When flow is annual cyclical, which is nearly always the case for unregulated streams, and violations of implicit assumptions of the exponential relationship (Equation (2)) cause deviations from expected behavior, the deviations should also tend to be annual cyclical.

Chemical data were developed for three gaged tributaries in Tahoe-Truckee system. Martis Creek near Truckee, California, which has a drainage area of about 41 square miles above the gaging station, drains directly into Truckee River. Until late spring 1971 there were no regulatory structures on Martis Creek. Sagehen Creek near Truckee, California, has a drainage area of 11 square miles above the gage. Little Truckee River drains about 38 square miles above the gaging station near Hobart Mills, California. Independence Lake, Weber Lake, and a diversion to Sierra Valley have a regulatory effect on flows of Little Truckee River. It is possible to adjust for diversions to Sierra Valley. Sagehen Creek is tributary to Little Truckee River at Stampede Reservoir. From Stampede Reservoir, Little Truckee River flows into Boca Reservoir and then into Truckee River.

Water samples from these streams were analyzed for ionic constituents and $SiO_2$. Thirty-nine samples were collected monthly from Martis Creek. Initially, samples from Little Truckee River near Hobart Mills and Sagehen Creek were collected bimonthly. Beginning in November 1969, sampling frequency was increased to a monthly basis, yielding a total of 27 and 28 samples for each stream, respectively.

Logarithmic plots of each constituent versus mean flow on the day during which the sample was collected show nearly linear relationships except for Cl and $SO_4$. Table 1 shows linear correlation coefficients for logarithms of flows for each stream. Figure 2 is a logarithmic plot of TDS concentrations versus flows at Martis Creek with a least squares regression line fit to the data. Except for Cl and $SO_4$, flow-concentration relations for all constituents in these streams are similar to the TDS-flow relation shown in Figure 2. Because of their unique behavior, prediction of Cl and $SO_4$ will be discussed separately.

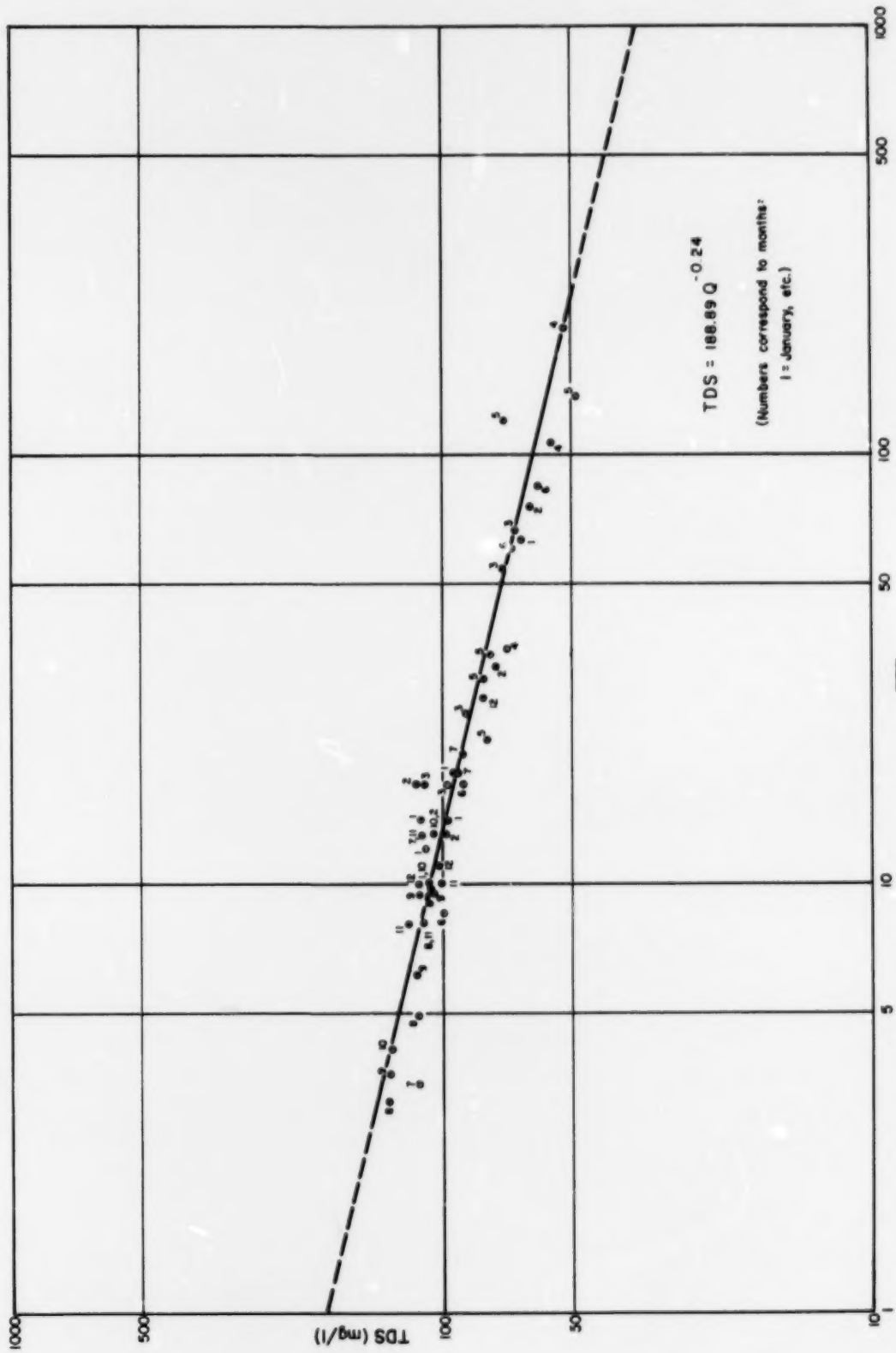


FIGURE 2. TDS-Flow Relation in Martis Creek.

## TABLE 1

### LINEAR CORRELATION COEFFICIENTS FOR LOGARITHMS OF CONCENTRATIONS VERSUS LOGARITHMS OF FLOWS (Martis Creek, Sagehen Creek, and Little Truckee River near Hobart Mills)

| | $HCO_3$ | Cl | $SO_4$ | Na | K | Ca | Mg | TDS | $SiO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| Martis Creek | -0.95 | 0.19 | 0.24 | -0.87 | -0.86 | -0.86 | -0.94 | -0.93 | -0.89 |
| Sagehen Creek | -0.99 | -0.16 | 0.12 | -0.96 | -0.96 | -0.98 | -0.98 | -0.99 | -0.88 |
| Little Truckee River | -0.94 | 0.00 | 0.04 | -0.90 | -0.89 | -0.94 | -0.94 | -0.95 | -0.44 |

The empirical relationship

$$C = aQ^{-b} \qquad (2)$$

satisfactorily explains most of the variance in concentrations of ionic constituents in the streams. For purposes of comparison with previously stated theoretical considerations, deviations from the regression line were examined for systematic behavior. For each of the streams, concentrations were plotted against flow rates on logarithmic paper by calendar year. There was no discernible time-systematic behavior of the deviations for any constituent at either Sagehen Creek or Little Truckee River. However, at Martis Creek all constituents showed a tendency for cyclic behavior of the deviations during some years.

Figure 3 is a logarithmic plot of TDS concentrations versus flows at Martis Creek which demonstrates cyclic behavior of the deviations during calendar year 1968. The cyclic effect was also present during 1969 and 1971 but was not as pronounced. Cyclic behavior was not present during 1970. Hydrographs of mean daily flows for calendar years 1968-1971 were examined to determine if systematic behavior of concentrations could be attributed to particular flow conditions. Although the 1970 hydrograph was markedly different than the others, it was not possible to explain the noncyclical behavior on the basis of this analysis. It is possible that construction operations for Martis Creek Dam in the vicinity of the sample site influenced water chemistry during 1970.

Because sample collection was discrete with respect to time (monthly intervals), it was not possible to make direct comparisons between concentrations at given flow rates on rising and falling limbs of dirurnal hydrographs. However, hydrographs of mean daily flows show base flow going from a minimum in midsummer to a maximum in late fall or early winter in response to progressively diminishing evapotranspiration (E.T.). At the same time, TDS concentrations decrease very slightly.

Plots of months 8-11 in Figure 3 are respresentative of conditions observed during 1968-1971. A line fit through base flow concentrations would be very much flatter than the regression line fitting data over the full range of flows. For this reason, behavior of base flow concentrations appears to be a deviation from expected behavior caused solely by a change in mass in the reach. Therefore, it appears that the base-flow regimen is governed by a different set of hydraulic conditions than those present during periods of direct runoff and interflow.

To verify presence of time systematic behavior over the entire period 1968-1971, data from the streams were subjected to statistical analysis. Regression equations expressing exponential relationships between concentrations and mean daily flows were used to estimate concentration of each constituent on sample collection days. In accordance with theoretical considerations and preliminary graphical analyses, differences between estimated and observed concentrations (first residuals) were analyzed for cyclical behavior. Although regression parameters a and b are statistically derived and cannot be exact values, it is likely that these parameters closely approximate underlying theoretical behavior. As such, they provide valid reference from which behavior of first residuals can be analyzed.

Statistical analyses performed on first residuals were serial correlation and nonparametric analyses consisting of runs (above and below median) test, turning points test, and Kendall's rank correlation. Serial correlation is a method for determining if series data have systematic time behavior. Resulting correlograms may reveal a behavior

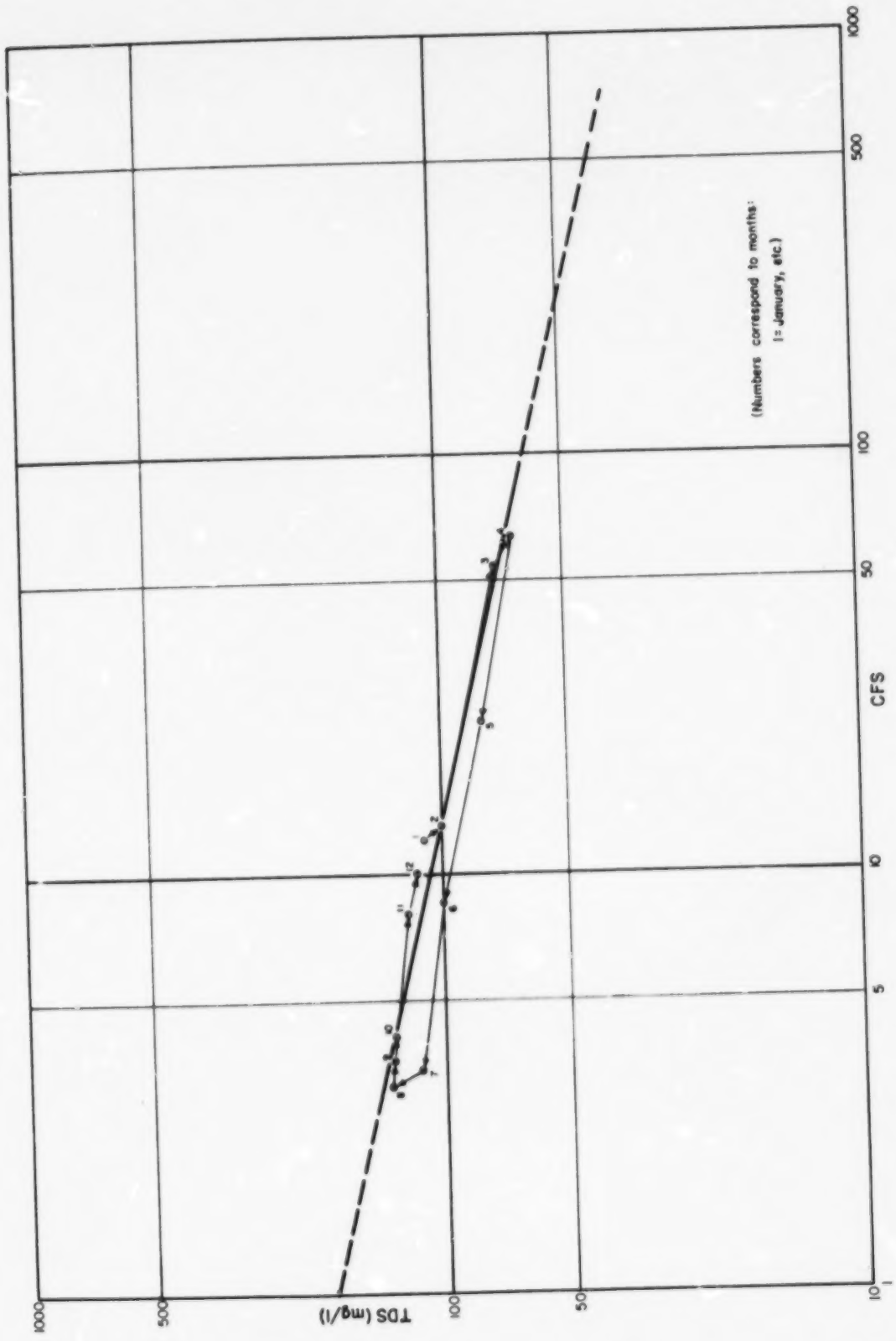


FIGURE 3. TDS Versus Flow in Martis Creek During 1968.

pattern which is not readily apparent by other analytical methods. Principal advantage of nonparametric tests is that they require no assumptions pertaining to type of frequency distribution of the data. The runs test is used to determine nonrandom behavior which may indicate either time trends or oscillatory (cyclical) patterns. The turning points test is used in conjunction with the runs test to infer nonrandom cyclical behavior. The rank correlation test is used in conjunction with the runs test to infer time trends by measuring the degree of association between the data and progression of time. Differentiation between oscillatory and cyclical behavior is by the serial correlation test.

Statistics used to test serial correlation coefficients were Anderson's standard normal variable (Anderson, 1942), Student's t, and Fisher Z transformation. The statistics were always corroborative and when at least two were significant at the five percent level of significance, the correlation coefficient was assumed to be significantly different from zero. The standard normal deviate was the statistic used for the nonparametric tests.

Results clearly showed first residuals at Sagehen Creek and Little Truckee River were random. However, at Martis Creek the tests were inconclusive and often contradictory. Nonparametric analyses indicated time trends for $HCO_3$, Mg, and TDS; cyclic or oscillatory patterns for Ca and $SiO_2$; and random behavior for Na and K. Except in the case of Mg, behavior was inferred from either turning points or rank correlation alone because the runs test was never significant at the five percent level of significance.

Although correlograms did not fit any of the classic behavior patterns, they did indicate that first residuals were nonrandom. The number of correlation coefficients significantly different from zero for each constituent ranged from three to eight. Their locations ranged from lags of one to twenty-six months with one always at lag one. There appeared to be a suggestion of Markovian behavior where the value of a given residual depends on the value of the preceding residual. Although this behavior is common in streamflow sequences, first residuals are independent from streamflow.

The only justifiable conclusion to be reached from the statistical analysis is that first residuals at Martis Creek are nonrandom with respect to time of year. Because each set contained only 39 data, it is possible that the apparent atypical behavior during 1970 was sufficient to mask underlying systematic behavior. For this reason additional graphical analyses were performed. First residuals at Martis Creek were averaged for each month over the period of record. Plots of first residuals are shown in Figure 4. Behavior of the average monthly first residual is clearly annual cyclical. Similar analysis at Sagehen Creek and Little Truckee River produced negative results.

On the basis of theoretical considerations and subsequent data analysis, general form of the equation used to estimate concentrations of dissolved minerals in Martis Creek is

$$C = aQ^{-b} + \bar{R}_i,\ i = 1, 12 \qquad (8)$$

where

$\bar{R}_i$ = mean first residual during the $i^{th}$ month, and
i = 1 in January, 2 in February, etc.

Although $\bar{R}_i$ may not be the true long-term monthly first residual, it is assumed to be a valid estimate because of the annual cyclical nature of runoff in Martis Creek. Equation (8) refers only to the explainable variance in the population of concentrations. The unexplained component (second residual) will be discussed in a later chapter.

Variation of Cl and $SO_4$ concentrations is not strongly associated with variations in flow. Analyses of 4 snow and snowmelt samples from the Martis Creek drainage indicate that Cl concentrations range from about 0.2 to 1.0 milligrams per liter mg/l). In the same samples, $SO_4$ concentrations range from 0.5 to 3.0 mg/l. This corresponds with concentrations reported from rain and snow samples on Spooner Summit, Highway 50, Nevada (Hem, 1970). Analyses of water samples from Sagehen Creek, Little Truckee River, and other streams above Highway 89 in California show Cl and $SO_4$ concentrations in this range. In general, geologic materials in upper Truckee Basin do not contain minerals from which Cl and $SO_4$ could be mobilized in high concentrations by water.

Although thermal waters are a possible source, their effect is probably minimal in upper Truckee Basin because there are few thermal springs. This indicates that Cl and $SO_4$ in these streams are principally precipitation derived. As such, the dilution concept implicit in the exponential relationship does not apply and concentrations of these constituents would not vary markedly with flow but would depend on climatologic, and perhaps snowpack conditions.

$SO_4$ concentrations in Martis Creek range from 0.5 to 3.1 mg/l,. about the same as for snow and snowmelt samples in the vicinity. However, Cl concentrations range from 0.82 to 12.65 mg/l. Analyses of water samples from perennial springs within Martis Creek drainage show Cl concentrations ranging from about 0.5 to 9.0 mg/l.

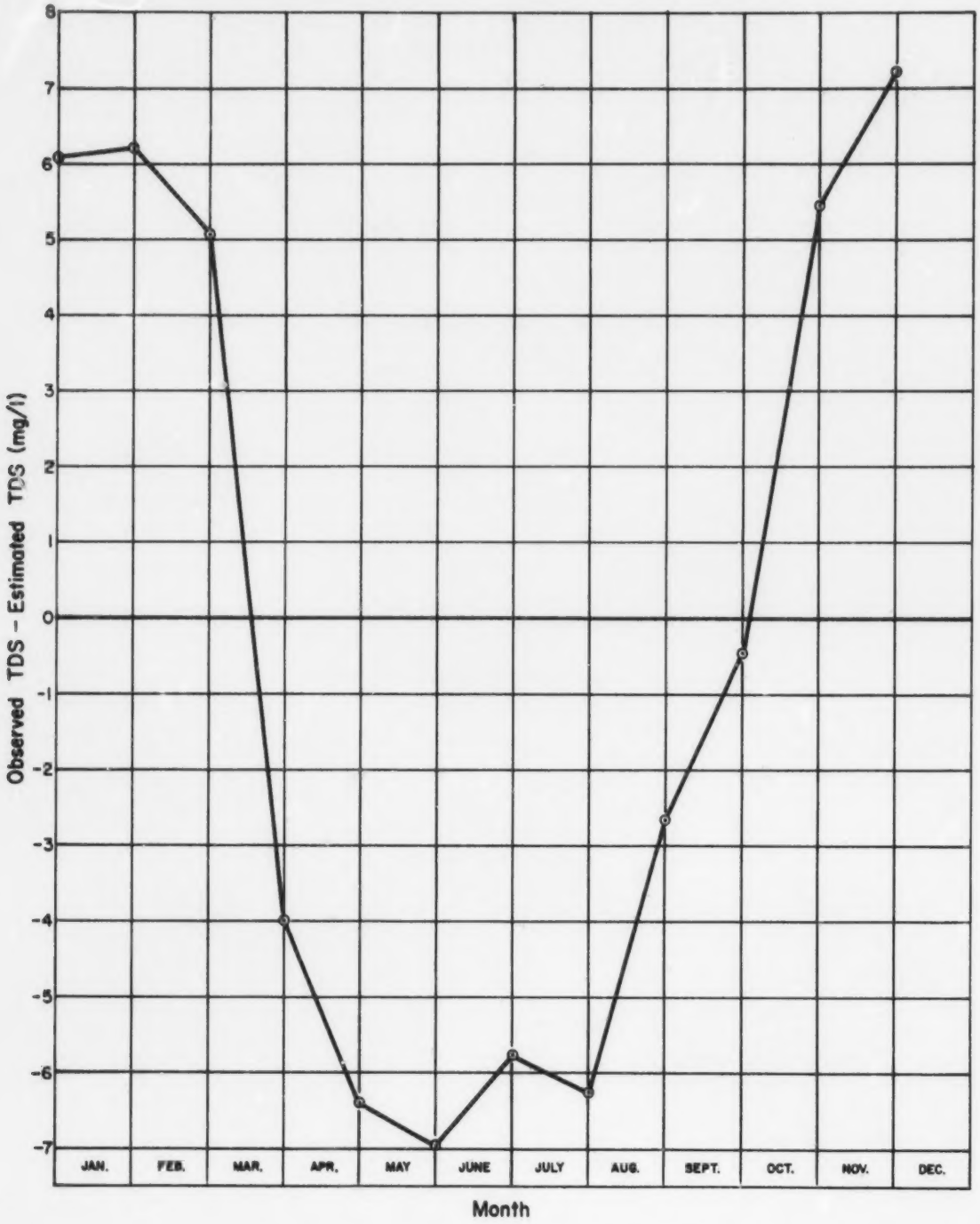


FIGURE 4. Average Monthly First Residuals of TDS at Martis Creek.

Therefore, geologic materials must be a source of Cl in Martis Creek and Cl concentrations should vary with flow according to the dilution concept.

The failure of Cl concentrations to exhibit flow dependence can be attributed primarily to the influence of road salt. The Martis Creek sample point is downstream from approximately 7 miles of all weather highway (California 267). Salt is commonly applied to this road during icy conditions. Figure 5 is a logarithmic plot of Cl concentrations versus flows in Martis Creek. The dashed line separates samples collected during winter months and snowmelt conditions from those collected at other times. Points plotted below the line reflect concentrations which cannot have been materially affected by road salt. Without influence of salt, Cl concentrations vary with flow in a manner similar to concentrations of other constituents. However, this relationship is not useful for quantitative description of Cl concentrations in Martis Creek.

The predictive equation used for $SO_4$ concentrations is purely empirical and for modeling convenience has the form of Equation (2). Although the predictive equation for C1 concentrations has the form of Equation (8), the concept of dilution should not be inferred except in an indirect manner. First residuals show a cyclical tendency which may reflect the seasonal nature of road salt applications. The combination of regression and additional cyclical component describes observed data better than does either a regression line or mean monthly value taken separately.

## REGULATED FLOWS

Dams on tributaries to Truckee River impound stream flow and regulate releases to the river. Because releases are controlled by operation of outlet structures, the exponential relationship between outflow and storage discussed in the previous section is not applicable and concentrations of dissolved constituents do not vary as a function of flow rate. Therefore, other predictive forms must be developed.

A number of regulatory structures exist on tributaries in Tahoe-Truckee system. Low outlet dams at Lake Tahoe and Donner Lake and Prosser and Boca Dams are relevant to this research.

As mentioned previously, Martis Creek Dam started impounding during late spring 1971. Subsequent data are too few to define new relationships for prediction of concentrations of dissolved constituents in outflows from the reservoir. Although predictive equations developed for the unregulated regimen appear to remain valid, additional data may show that new relationships exist. However, because it was constructed for flood control, storage will be minimal. Therefore, it is also possible that established predictive relationships will remain valid.

Concentrations versus flows and concentrations versus time were plotted on scatter diagrams for each constituent at each of the four dam sites. As expected, flow-concentration relationships were nearly nonexistent. At Boca and Prosser Reservoirs, time-concentration relationships for most constituents were annual cyclical. At Tahoe City, time-concentration relationships appeared to be annual cyclical for some constituents although amplitudes were very low. At Donner Lake, concentrations appeared to be relatively constant.

Cyclical behavior of chemical quality of outflows is probably a response to inflows whose quality is also annual cyclical. In any given year, flow through the reservoirs is usually 2.5 or more times greater than useable storage space behind the dams. Minimum pools in Prosser Reservoir each year depend on anticipated storage requirements for spring runoff and are usually less than 30 percent of the total storage capacity.

Boca Reservoir was operated in a similar manner prior to operation of Stampede Reservoir. Minimum pools were attained earlier in the year and amounted to less than five percent of the storage capacity. Since Stampede Reservoir has become operational, operating rules at Boca Reservoir have changed with minimum pools now increased to between 45 and 70 percent of the storage capacity.

Annual releases from Lake Tahoe are less than half the useable storage behind the dam and only a small fraction of the total volume of the lake. Although chemical quality of runoff undoubtedly varies according to location around the lake, records show that annual hydrographs of mean monthly flows have similar shapes regardless of location of the stream. This indicates that highest quality water enters the lake at one time and poorest at another which should, according to the annual cyclical nature of runoff, impose an annual cyclical water quality pattern on the lake. However, the large lake area (about 122,000 acres) and storage volume (735,000 ac/ft in the upper 6 ft.) apparently contribute to a relatively long residence time and considerable mixing of inflow such that the cyclical behavior of chemical quality at the outlet is damped compared to fluctuations observed at individual tributary streams such as Blackwood Creek.

Storage records indicate that operation of Donner Lake is similar to Prosser and Boca Reservoirs. During the period of this research, annual outflows have ranged from 1.4 to more than 3 times the storage capacity. Minimum pools have apparently ranged from 31 to 37 percent of the storage capacity. Records of inflow quality and volume

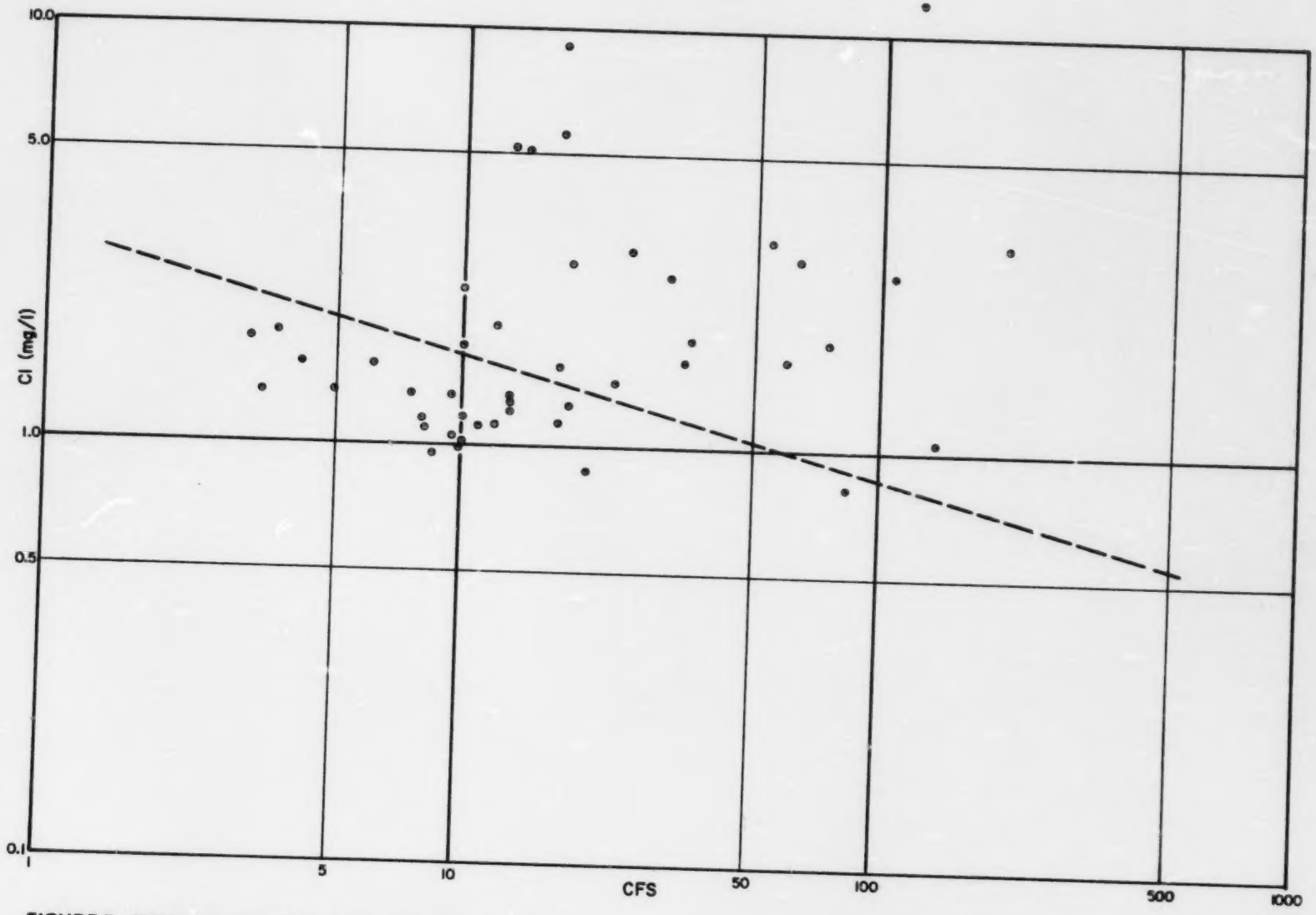


**FIGURE 5. Cl Concentrations Versus Flows in Martis Creek.**

do not exist. By inference from behavior of other streams and reservoirs in the basin, chemical quality of outflows should be annual cyclical instead of constant with respect to time. Incomplete storage records, relatively short record of chemical quality (24 months), and absence of inflow data prevent further analysis or verification of this apparently anomalous behavior.

Chemical quality of releases from Boca and Prosser Reservoirs appeared to respond, at least in part, to reservoir operating procedures. Therefore, a multivariate scheme was envisaged for prediction of outflow concentrations. Because operating rules can be prescribed, those geometric parameters which reflect state of the reservoir were examined as potential predictor variables. Inflows, as the source of dissolved constituents, were also evaluated for predictive value. The sequence of development for predictive equations was 1) enumeration of possible predictor variables with selected combinations and permutations, 2) analysis for predictive value and inner dependence of predictors, and 3) multiple regression on those variables having significant predictive value.

Data were insufficient for development of equations relating chemical quality of outflows to mixing processes in the lakes and reservoirs. However, by assuming complete mixing it was possible to derive an analytical expression relating chemical quality of reservoir releases to inflow quality, reservoir storage, and inflow. The expression is

$$C_t = C_i + (C_b - C_i)\,(S_o/S_t)^{I/\Delta S} \qquad (9)$$

where

$C_t$ = concentration of dissolved constituent in release at time "t" ($M/L^3$);
$C_b$ = initial concentration of dissolved constituent in the release ($M/L^3$);
$C_i$ = average concentration of dissolved constituent in inflow during interval zero to "t" ($M/L^3$);
$S_o$ = initial reservoir storage ($L^3$);
$S_t$ = reservoir storage at time "t" ($L^3$);
$I$ = inflow volume during interval zero to "t" ($L^3$); and
$\Delta S$ = storage change in reservoir during interval zero to "t" ($L^3$).

Equation (9) expresses mass balance in a completely mixed reservoir having an initial mass of dissolved constituent, constant flux of constituent into the reservoir, and a fixed rate of release of the solution from the reservoir. Flux and release rates are assumed to be constant over the time interval of interest.

Although mixing processes are not known, they are undoubtedly influenced by reservoir geometry. Inflows must transfer the bulk of their momentum into turbulence and mixing upon entry into an impoundment. Energy transfer must occur within some distance from the point of entry. Mean depth, mean surface area, and ratio of mean area to mean depth were postulated as parameters relating to the energy transfer. Conceptually, mean depth relates to vertical mixing, area relates to longitudinal and transverse mixing, and the ratio of area to depth relates to the shape of the vertical cross section. Mean storage was postulated as a predictor variable representative of the mass available to absorb inflow momentum. Storage change was selected as an alternative variable to storage ratio ($S_o/S_t$ in Equation (9)) to account for the effect of storage variability on mixing.

As noted earlier, flow-concentration relations were nearly nonexistent at reservoir outlets. However, data collected at Boca Reservoir subsequent to the beginning of operation of Stampede Reservoir do show that concentrations vary as a function of release rate. This is a result of the change in operating rules for Boca Reservoir. Therefore, release rate was considered as a possible predictor variable at Boca Reservoir for the period after completion of Stampede Dam.

Because inflow during any given year is usually at least 2.5 times useable storage capacity, reservoir operations can be viewed as a device for delaying streamflows and throughputs of dissolved constituents. The annual cyclical variation of concentrations of constituents in releases supports this contention. Therefore, to account for the possibility of systematic delay in routing masses of dissolved constituents through the reservoirs, time-lagged storage volumes and estimated inflow concentrations were considered as possible predictor variables.

Estimates of inflow concentrations at Prosser Reservoir were based on regression equations developed from six pairs of flow and chemical quality data collected at Prosser Creek above the reservoir. Because flows upstream from the reservoir are not measured continuously, inflow concentrations were estimated using average monthly inflow rates as derived from continuity considerations at the reservoir. Water samples were not collected from Little Truckee River at the U.S.G.S. gaging station above Boca Reservoir near Boca, California until shortly before Stampede Reservoir became operational. Estimates of inflow concentrations to Boca Reservoir were based on regression equations developed from flows measured at the U.S.G.S. gage and are representative only of the post-Stampede Reservoir period.

To reduce the number of variables under consideration as potential predictors, estimated inflow concentrations were screened for predictive value. Serial correlation techniques were used to determine association of estimated inflow concentrations to outflow concentrations at each reservoir. At Prosser Reservoir, analyses showed highest correlations at lags of three and four months for all constituents except Cl and $SiO_2$. This indicates that a given mass influx produces a response at the reservoir outlet in approximately three to four months. Significant negative correlations at multiples of 12 months after lags 3 and 4 are caused by annual cyclical behavior of inflow concentrations.

Cl and $SiO_2$ concentrations show highest association at lags of six to eight months and both inflow and outflow appear to have an annual cyclical fluctuation. However, it is probable that the correlations and behavior are fortuitous. The volume of water released from the reservoir over an interval of six months is at least as great as the useable storage capacity. If the behavior is related to reservoir operations, mechanisms causing the behavior are not readily apparent. Therefore, in the interests of stability for predictive purposes, inflow concentrations at lags of six months or greater were not used as predictor variables.

At Boca Reservoir, outflow quality was based on analysis of 21 monthly samples collected prior to operations at Stampede Reservoir and a like number collected afterwards. Because a data length of 21 is generally marginal for correlation analysis, the entire data string was used. Correlation between inflow and outflow concentrations were best at lags 0 to 2 months for all constituents except Cl, $SO_4$, and $SiO_2$. Although serial correlation coefficients were not as high as those calculated for Prosser Reservoir, they were statistically significant. The 12-month periodicity in the correlogram was due to annual cyclical behavior of inflow concentrations. Meaningful correlations and systematic behavior were both absent in the cases of Cl, $SO_4$, and $SiO_2$ concentrations.

Due to change in operating criteria at Boca Reservoir, two sets of predictive relationships appeared necessary. One additional set was required for Prosser Reservoir. Each of the three sets of predictors had to consist of nine equations, one for each constituent. Although the possible predictor variables have been discussed, functional relationship between outflow concentrations and possible predictor variables was unknown. To keep data handling and analysis within confines of time and predictive accuracy, it was necessary to make two important assumptions. First, functional relationship between outflow concentration and any particular variable was assumed to be either linear or logarithmic in the predictor variable. Second, it was assumed that all conservative substances must behave similarly. Therefore, a set of predictors must utilize the same basic variables for each constituent.

Because behavior of TDS concentrations in reservoir releases reflected the behavior of component ionic constituents (except for Cl, $SO_4$), TDS was selected as the dependent variable for development of predictive equations. $SiO_2$ was assumed to conform to the predictive variables for TDS. This reduced analysis of predictor sets to one equation per set. For each of the three sets of predictors, the appropriate variables and their logarithms were subjected to multiple correlation analysis together with TDS to determine which variables had predictive value.

Multiple regression equations tend to increase in stability and predictive capability with increasing independence of the individual predictor variables. Sorting through a correlation matrix, even those which are relatively small, to select those variables which correlate with the dependent variable but correlate least with other predictors is an arduous, if not impossible task. To circumvent this problem, those variables having a partial correlation coefficient with TDS which seemed to be significantly different from zero were subjected to principal component analysis (Kendall, 1957) followed by varimax rotation (Kaiser, 1958).

Factors resulting from principal component analysis are orthogonal but loadings for any given variable are not comparative between factors. Therefore, it is difficult to tell on which factor a given variable lies. Rotated factors yield comparative loadings, but the factors are not mutually orthogonal. To test the significance of rotation versus nonrotation on this analysis, loadings on the nonrotated factors were reduced to standard measure for the Boca set of pre-Stampede variables. Although there were some differences between locations of variables in the two sets of factors, those variables having the highest loadings appeared to fall on the same factor regardless of rotation. For economy of effort, varimax rotation was considered adequate for analysis of variable independence.

That variable having the highest loading on a given factor was selected as an "independent" predictor variable. Although these variables had the least amount of interdependence, none were truly independent. These variables are listed according to predictor set in Table 2. Each set of variables for each of the nine constituents was then subjected to stepwise multiple regression analysis. Final formulation of predictive equations can be expressed as

$$C_t = K_o + \Sigma K_i V_i \qquad (10)$$

where

$C_t$ = outflow concentration from the reservoir at time t;
$K_o$ = ordinate intercept;
$K_i$ = $i^{th}$ regression coefficient;
$V_i$ = $i^{th}$ predictor variable; and
i = variable index ranging from 1 to n variables.

Results show that predictive capabilities as indicated by multiple correlation coefficients are relatively good. Correlation coefficients for each constituent at each reservoir are shown in Table 3. Within each predictor set, the relative importance of a given variable may differ for different constituents. This is probably due to redundancy caused by interdependence between predictor variables rather than being a contradiction to the similarity of behavior assumption.

## TABLE 2

## PREDICTOR VARIABLES FOR RESERVOIRS

**BOCA RESERVOIR (Pre-Stampede Reservoir)**

1. Ratio of inflow to storage change ($I/\Delta S$)
2. Logarithm of mean storage (Log $\bar{S}$)
3. Logarithm of inflow (Log I)
4. Logarithm of ratio of initial to final storage (Log $S_o/S_t$)
5. Logarithm of ratio of mean surface area to mean depth (Log $\bar{A}/\bar{D}$)
6. Logarithm of storage ratio raised to $I/\Delta S$ power (Log $(S_o/S_t)^{I/\Delta S}$
7. Initial concentration of dissolved constituent in release ($C_o$)

**BOCA RESERVOIR (Post Stampede Reservoir)**

1. Estimated average concentration in inflow 2 months previous ($C_{i\text{-}2}$)
2. Estimated average concentration in inflow 1 month previous ($C_{i\text{-}1}$)
3. Estimated average concentration in inflow ($C_i$)
4. Ratio of initial to final storage ($S_o/S_t$)
5. Final storage ($S_t$)
6. Storage change ($\Delta S$)
7. Logarithm of release rate (Log $Q_{r,\,t}$)
8. Initial concentration of dissolved constituent in release ($C_o$)

**PROSSER RESERVOIR**

1. Estimated average concentration in inflow 4 months previous ($C_{i\text{-}4}$)
2. Estimated average concentration in inflow 3 months previous ($C_{i\text{-}3}$)
3. Ratio of initial to final storage ($S_o/S_t$)
4. Average surface area ($\bar{A}$)
5. Inflow (I)
6. Initial concentration of dissolved constituent in release ($C_o$)

## TABLE 3

## CORRELATION COEFFICIENTS FOR RESERVOIR PREDICTIVE EQUATIONS

| Constituent | Boca Reservoir (Pre-Stampede) | Boca Reservoir (Post Stampede) | Prosser Reservoir |
|---|---|---|---|
| $HCO_3$ | 0.92 | 0.77 | 0.91 |
| Cl | 0.88 | 0.55 | 0.37 |
| $SO_4$ | 0.73 | 0.46 | 0.55 |
| Na | 0.93 | 0.60 | 0.70 |
| K | 0.90 | 0.88 | 0.77 |
| Ca | 0.93 | 0.75 | 0.87 |
| Mg | 0.87 | 0.72 | 0.78 |
| $SiO_2$ | 0.75 | 0.82 | 0.64 |
| TDS | 0.92 | 0.81 | 0.89 |

Inspection of the data showed that in Little Truckee River below Boca Reservoir concentrations of all constituents were anomalously high when release rates dropped below 0.5 cfs. This is probably the result of seepage through the dam. In a predictive sense, whenever low-flow conditions are met, out-flow concentrations are set to the average previously observed.

For operating purposes, surface area of Lake Tahoe is assumed to be constant within range of useable storage. Area-capacity curves have not been developed. Although selected streams are gaged, they do not constitute the entire flow into the lake. Back-calculation of inflows from releases and storage changes is complicated by unmeasured diversions from the basin, export of treated effluent, and evaporation from the 122,000 acre surface of the lake. Because depth and storage are directly proportional to lake elevation, variables which relate to mixing and can be calculated from existing data or are measured directly are lake elevation, elevation changes, and release rates. Scatter diagrams show no correspondence between these variables and concentrations of dissolved constituents in releases.

In the case of the reservoirs, a time lag or routing concept was considered in relating water-quality responses at the outlet to influx of dissolved constituents. Chemical quality of inflow to Lake Tahoe is not known. However, gaged streams tributary to the lake have hydrographs of similar shape. Because of the logarithmic relationships between flows and concentrations in unregulated streams in the basin, it was inferred that concentrations in Blackwood Creek, about 4.6 miles south of Tahoe City, would behave similarly to chemical quality of other streams tributary to the lake. To test the hypothesis that concentrations of dissolved constituents in releases from Lake Tahoe were lagged responses to influxes of dissolved minerals to the lake, serial correlation techniques were used to determine association of chemical quality of Blackwood Creek to that of Truckee River near Tahoe City, California.

During the period of research, only 15 water samples were collected from Blackwood Creek. To circumvent the problem of commensurate data at the two points of interest, flow-concentration regression equations were developed for Blackwood Creek. In turn, these equations were used to estimate concentrations for the same days in which Truckee River near Tahoe City was sampled.

Correlation analysis showed a strong correspondence between estimated concentrations in Blackwood Creek and observed concentrations in Truckee River for all constituents except Cl, Ca, and $SiO_2$. Behavior is annual cyclical; however, there is no time displacement between responses at the two points. It is likely that concentrations of dissolved constituents in releases from Lake Tahoe are responses to influxes of dissolved minerals in runoff occurring in the general vicinity of Tahoe City. Damping without time displacement occurs through mixing in the relatively large body of receiving water in Lake Tahoe in the vicinity of the dam.

Because amplitude of the fluctuations was small, it was not possible to verify by graphical methods the presence or absence of cyclical or nonrandom oscillatory behavior of individual constituents in releases from Lake Tahoe. To test if systematic behavior were statistically observable, data were subjected to nonparametric and serial correlation analyses in the same manner as previously discussed in the section on unregulated flows. Only $HCO_3$ and TDS concentrations showed statisical evidence of cyclical behavior.

Concentrations of each constituent were averaged by month and average values were plotted in a time sequence of 12 months. All constituents except Cl, Ca, and $SiO_2$ showed annual cyclical behavior similar to that shown in Figure 6 for Na concentrations. $SO_4$ behavior is inverse to the pattern exhibited by other constituents. Although $SO_4$ concentrations are less than 5 mg/l, they are usually at least 3 mg/l. Because concentrations are usually equal to or greater than the upper limit reported for precipitation (Hem, 1970) and the behavior pattern is dissimilar to that of other ionic constituents having sesonal behavior, it is doubtbul that there is a seasonal variation.

At Tahoe City, fluctuation of concentrations of dissolved constituents is small. Standard deviations are approximately equal to the range of analytical error for each constituent. Although runoff characteristics are similar from year to year, volume, duration, and time of peak discharge are variable. Concentrations of flow-dependent constituents do not necessarily reach extremel values during the same months every year. Small fluctuations in concentrations of individual constituents combined with variability in time displacement of maximum and minimum concentrations from year to year tend to mask annual cyclical behavior. When compared with other data which are influenced by the same runoff producing conditions, the cyclical behavior is clear. The monthly averaging technique also tends to minimize the effect of an atypical runoff condition during a given year.

It is demonstrable that even though volumes and rates of runoff may vary considerably, the time distribution of runoff in unregulated streams adjacent to Lake Tahoe is remarkably consistent from year to year. As a result, concentrations of flow dependent constituents will be greatest during the low-flow periods of fall and winter and least during spring runoff. Therefore, prediction of concentrations of those constituents exhibiting seasonal variation vis-a-vis correlation with data at Blackwood Creek and the monthly averaging technique is based on average concentrations for each month. These constituents are $HCO_3$, Na, K, and TDS.

The average of all observations of each constituent is used as the predicted value for Cl, $SO_4$, Ca, Mg, and $SiO_2$. Except for $SO_4$, variation in concentrations of these constituents appears to be random. Random behavior of Ca, Mg, and $SiO_2$ concentrations cannot be explained satisfactorily at this time. Cl and $SO_4$ concentrations lack flow dependence in other streams observed in Tahoe-Truckee system during this research. However, the influence of road salt on Cl concentrations seen in other streams is not observable at Lake Tahoe.

As mentioned previously, storage records at Donner Lake are incomplete. Lake elevations during winter months are usually not recorded because the lake is frozen. During the remainder of the year, lake elevations are recorded infrequently and at nonperiodic intervals. In addition, there are not data pertaining to inflow rates or inflow chemistry. Data inadequacies preclude most analytical procedures employed for the reservoirs and Lake Tahoe.

Concentrations of individual constituents as measured near the U.S.G.S. gaging station on Donner Creek near Donner Lake failed to show correspondence with either release rates or with estimated inflow to Donner Lake. Except for two observations, concentrations of individual constituents in releases appeared to be nearly constant with only token random variation. One of the anomalous observations consisted of abnormally low concentrations of ionic constituents where values were nearly one half of the normal observed value. There is no apparent explanation for this behavior. The other anomalous observation consisted of an abnormally highly mineralized sample collected when release rate from Donner Lake was only 1.4 cfs. The increased mineralization was probably due to the relatively large component of ground-water accretion to the stream in the reach between the lake and sample site.

Prediction of concentrations in releases from Donner Lake is based on average of all observations of each constituent, excluding the anomalous observations. Whenever release rates fall below 1.5 cfs, average concentrations are replaced by the abnormally high concentrations previously observed during the minimum flow conditions.

Although Donner Lake has an important regulatory influence on flows and chemical quality of Donner Creek, other factors have an important effect on flux of dissolved constituents entering Donner Creek at its confluence with Truckee River. Donner Creek flows are measured at a gaging station approximately two miles upstream from Truckee River. Cold Creek, which has a drainage area approximately equal to the Donner Lake drainage, flows into Donner Creek about one-quarter mile below the gaging station. Cold Creek flows are not measured. During the spring there is considerable runoff directly into the reach below the gage. Interstate Highway 80 as well as commercial and domestic developments are part of this contiguous drainage.

During years 1929 through 1943 there were stream gages on Donner Creek above and below the confluence with Cold Creek. It was possible to get monthly volumes in Cold Creek by difference and to correlate these flows with estimated unregulated flows at Farad, California. Cold Creek was gaged and sampled eight times during 1970 and resultant data were used to establish flow-concentration relations for all constituents. To estimate concentrations of individual constituents in Cold Creek, Cold Creek flows are first estimated from the regression equation relating Farad unregulated flows to Cold Creek flows. The flow estimate is then used in flow-concentration

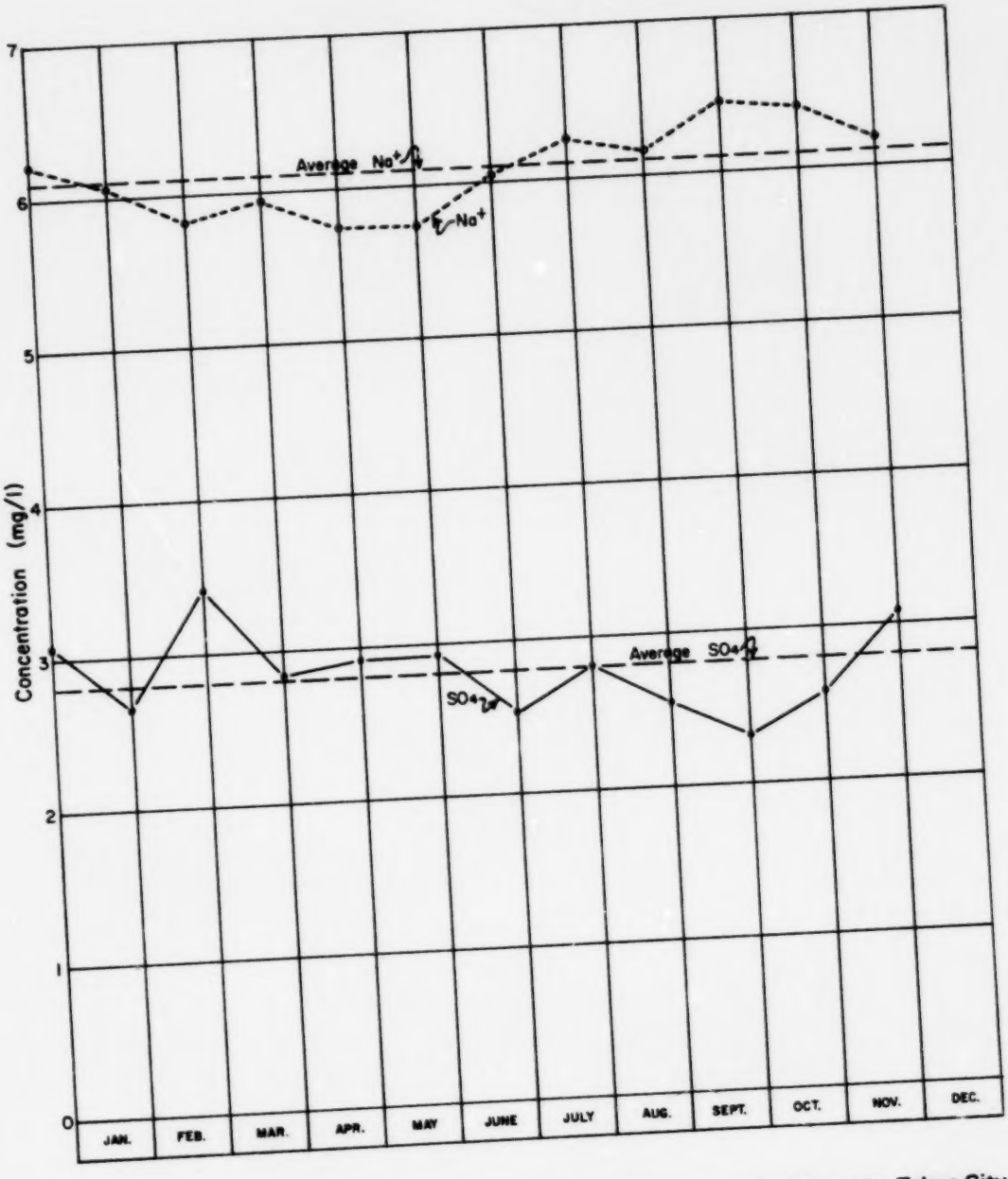


**FIGURE 6. Average Monthly Concentrations of Na and $SO_4$ in Truckee River near Tahoe City.**

regression equations to estimate concentrations.

According to principles of mass flux balance described in the section pertaining to the conceptual model, estimated flux in Cold Creek is added to estimated flux in Donner Creek above Cold Creek. Concentrations derived by dividing total flux by total flow consistently underestimate concentrations observed in Donner Creek near its confluence with Truckee River. The increase can be attributed to unmeasured accretions to Donner Creek in the reach below Cold Creek. Differences between estimated and observed concentrations appear to vary randomly about a mean value for each constituent. Final estimates of concentrations in Donner Creek at its confluence with Truckee River are made by adding the mean difference for each constituent to the original estimates. Residual errors are comparatively large but are random about a mean of approximately zero. Final errors can be attributed principally to unexplained variance in equations used to estimate flows in Cold Creek, concentrations in both Cold Creek and Donner Creek above Cold Creek, and variation in the dispersed input below Cold Creek.

## DISPERSED FLOWS

Dispersed flows are net unmeasured accretions to or depletions from the mainstem. They may be surface water, ground water, or a combination. In a given reach, accretions and depletions may be occurring simultaneously in any gain/loss proportion and the proportion may vary with time. Both dispersed flows and dispersed fluxes in a reach can be calculated as differences between measured inputs and outputs. However, individual components of dispersed flows and fluxes are indeterminable.

For purposes of establishing predictive relationships in Tahoe-Truckee system, only three general cases need be considered. They are 1) continuous accretions to the mainstem from tributary streams, 2) continous accretions from diffuse ground-water sources, and 3) the situation where gains and losses may occur in any combination via either surface conveyances or exchanges with a contiguous aquifer, or both. In the absence of accretions, concentrations in the mainstem remain constant. In all cases, evaporation has negligible influence on concentrations of dissolved constituents.

Consider case (1) where dispersed flow consists entirely of accretions from tributary streams along a reach of the mainstem. Assume that each stream has a dispersed flow-concentration relation of the form

$$C_i = a_i Q_i^{-b_i} \qquad \text{(2) or (11)}$$

where

i = a subscript referring to a specific tributary.

Further assume that tributary flow rates are all proportional so that flow rates in any tributary can be expressed in terms of flow rates in one particular tributary. Then

$$Q_i = K_i Q_j \qquad (12)$$

where

K = a proportionality constant, and
j = one specific tributary.

Then by combining Equations (11) and (12) concentration in tributaries can be expressed as

$$C_i = a_i K_i^{-b_i} Q_j^{-b_i} \qquad (13)$$

Flux is the product of flow and concentration and can be expressed as

$$F_i = C_i Q_i$$

or by combining Equations (12) and (13) as

$$F_i = a_i K_i^{1-b_i} Q_j^{1-b_i} \qquad (14)$$

where

F = flux (M/T).

Total dispersed flow can be expressed as

$$Q_{Disp} = Q_j \sum_{i=1}^{n} K_i \qquad (15)$$

Dispersed concentrations can be calculated as dispersed flux divided by dispersed flow as expressed by

$$C_{Disp} = \frac{\sum_{i=1}^{n} F_i}{\sum_{i=1}^{n} Q_i} \qquad (16)$$

where

$C_{Disp}$ = concentration in dispersed flow ($M/L^3$).

By substituting Equations (14) and (15) into Equation (16) and cancelling terms, dispersed concentrations can be expressed as

$$C_{Disp} = \frac{\sum_{i=1}^{n} a_i K_i^{1-b_i} Q_j^{-b_i}}{\sum_{i=1}^{n} K_i} \qquad (17)$$

For purposes of comparing equation forms, let regression coefficients ($b_i$) for a given constituent be identical for all tributaries. Then Equation (17) can be expressed as

$$C_{Disp} = \frac{\sum_{i=1}^{n} a_i K_i^{1-b}}{\sum_{i=1}^{n} K_i} \cdot Q_j^{-b} \qquad (18)$$

Rearranging Equation (15) and substituting, the expression for dispersed concentration becomes

$$C_{Disp} = \frac{\sum_{i=1}^{n} a_i K_i^{1-b}}{\sum_{i=1}^{n} K_i \cdot \left[\sum_{i=1}^{n} K_i\right]^{-b}} \cdot Q_{Disp}^{-b} \qquad (19)$$

Under prevailing assumptions, the ratio of summations is constant valued and the form of Equation (19) is identical to that of Equation (11). When underlying assumptions are violated, Equation (19) is technically invalid. However, in practical terms constraints may be relaxed to a considerable degree and the line of best fit for the data will have the same form as Equation (19).

In case (2), constant gains from diffuse ground-water sources, the simplest assumption is invariant concentrations in the ground water. A second, more tenable hypothesis recognizes the possibility of systematic temporal behavior with regard to both ground-water flow and quality. Water levels in wells, flow from springs, and

chemical quality of water from these sources commonly show either trend or cyclic (oscillatory) behavior, or both. Therefore, it is possible that dispersed flows and concentrations of dispersed flows will show either cyclic (oscillatory) tendencies, time trends, or both. In Tahoe-Truckee system, at springs showing annual cyclical behavior of flow and quality, the largest variations appear in those springs receiving local recharge from precipitation (Bateman, 1970). Marked cyclical behavior of dispersed flows and concentrations could be expected if there were a source of local recharge (e.g., from irrigation adjacent to the river).

It is difficult to imagine conditions which would preclude a river from transmitting water into bank storage during peak flows. During flood stages gradients are reversed and water is transmitted from the river to adjacent sediments. If overbank flooding occurs, then there may be local recharge to the ground-water system via spreading on bench lands. When river stage subsides, injected water will flow as ground water toward the river.

According to Darcy's Law, apparent velocity of ground-water flow is proportional to the hydraulic gradient which can be expressed as

$$I = \frac{dh}{dx} \tag{20}$$

where

I = hydraulic gradient,
h = hydraulic potential (L), and
x = distance along the flow path (L).

Recoveries of water levels in pumped wells or injection wells are often related exponentially or logarithmically to time. If floods are the only source of recharge and recharge events are of relatively short duration, then subsequent decay of water levels in the aquifer can be considered to be a function of time. If water levels decline exponentially with time, then hydraulic gradient can be expressed as

$$I = Mt^{-m} \tag{21}$$

where

t = time (T),
m = exponent describing rate of decay, and
M = an arbitrary proportionality constant.

If the water-level declines are logarithmic, then hydraulic gradient can be expressed as

$$I = A - B \log t \tag{22}$$

where

A = ordinate intercept, and
B = rate of change of I with respect to the logarithm of t.

Ground-water seepage into a stream reach can be expressed according to Darcy's Law as

$$q = KIT_a \tag{23}$$

where

q = flow rate per unit length of stream channel ($L^2/T$),
K = hydraulic conductivity (L/T), and
$T_a$ = vertical thickness through which flow occurs (L).

Substituting for exponential decay of hydraulic gradient as shown in Equation (21) and solving for time, Equation (23) becomes

$$t = \frac{q^{-1/m}}{(KMT_a)^{-1/m}} \tag{24}$$

Substituting into Equation (23) the logarithmic expression for hydraulic gradient shown in Equation (22) and solving for time yields, the expression

$$t = 10^{\frac{1}{B}(q/KT_a - A)} \tag{25}$$

Now assume that concentration in the ground water is a function of time and can be expressed as

$$C = Kt^n + C_o \tag{26}$$

where

$C$ = concentration of dissolved constituent in the ground water ($M/L^3$),
$C_o$ = initial concentration of dissolved constituent in recharged water ($M/L^3$),
$k$ = proportionality constant, and
$n$ = exponent whose value is greater than zero and may be equal to 1.

If the exponential expression for time shown in Equation (24) is substituted in Equation (26), concentration can be expressed as

$$C = \frac{K}{(KMT_a)^{-n/m}} \cdot q^{-n/m} + C_o \tag{27}$$

Rearranging slightly, Equation (27) becomes

$$C = \frac{K}{(KMT_a)^{-n/m}} \cdot (q + C_o')^{-n/m} \tag{28}$$

where

$C_o' = C_o^{-m/n}$ .

Equation (28) is similar to Equation (11). However, as flow rates diminish the influence of the initial concentration may become important whereas at higher flow rates it can be disregarded.

If the substitution for time in Equation (26) is according to the logarithmic relationship shown in Equation (25), the expression for concentration becomes

$$C = K\,10^{\frac{n}{B}(q/KT_a - A)} + C_o \tag{29}$$

Equation (29) is logarithmic in terms of $C$ or $(C-C_o)$. Therefore, the dispersed ground-water flow-concentration relation may be logarithmic in form if the relationship between decline of water level and time is logarithmic.

Case (3), where a reach may gain and lose simultaneously through both ground- and surface-water interchanges with the mainstem, may be the most realistic case. As regards this general case, it may be advisable to look for a systematic relationship between dispersed flux and dispersed flow. Within the context of mass-flux balance, this concept permits accounting for a variety of flux and flow conditions, a versatility not present in hypotheses presented in discussion of the two previous general cases. However, systematic behavior presumes a fixed relationship between the factors which produce flux and flow responses. In this respect, the flux-flow concept is no more valid than other predictive forms. Because underlying mechanisms are not understood, extrapolations beyond the data base are tenuous and constitute the major disadvantage of this predictive approach.

On the basis of stream gaging stations on the mainstem, Truckee River was divided into six reaches for simulation of dispersed flux or concentrations of dissolved constituents in dispersed flows. Reaches are as follows:

1. From the U.S. Geological Survey stream gaging station (hereafter referred to as gaging site) No. 10337500 at Tahoe City, California, to the defunct gaging site near Truckee, California, (Tahoe-Truckee reach).
2. From the defunct gaging site near Truckee, California, to gaging site No. 10346000 at Farad, California (Truckee-Farad reach).

3. From the Farad gaging site to gaging site No. 10350000 at Vista, Nevada (Truckee Meadows reach).
4. From the Vista gaging site to gaging site No. 10351600 below Derby Dam, Nevada (Vista-Derby Dam reach).
5. From the Derby Dam gaging site to gaging site No. 10351650 at Wadsworth, Nevada (Derby Dam-Wadsworth reach).
6. From the Wadsworth gaging site to gaging site No. 10351700 near Nixon, Nevada (Wadsworth-Nixon reach).

Preliminary to further analysis, the six reaches can be classified into four general categories according to major factors influencing dispersed fluxes and flows. Both Tahoe-Truckee and Truckee-Farad reaches are primarily gaining reaches whose sources of dispersed flow and flux are principally ungaged and unregulated surface tributaries. Truckee Meadows reach is characterized by diversions for municipal and agricultural use and inflows from agriculture, hot springs, regional ground-water flow systems, urban runoff, a sewage treatment plant, and tributary streams. Gain-loss regimens of Vista-Derby Dam and Derby Dam-Wadsworth reaches are determined principally by 1) minor diversions for irrigation of lands adjacent to the river and their subsequent return (less E.T.) to the river as irrigation tail water and as ground water, and 2) temporary recharge to and release from bank storage. In Derby Dam-Wadsworth reach, the gain-loss regimen is further complicated by operating procedures in Truckee Canal. Two emergency wasteways were constructed in the canal downstream from the gaging station for protection of the railroad. Use of these wasteways for regulation of flows in the canal results in returns directly to the river downstream from the gaging station near Derby Dam. The Wadsworth-Nixon reach is primarily a gaining reach whose principal source of dispersed flux and flow is discharge from regional ground-water flow systems.

Chemical quality of dispersed flow is calculated by differences. Although the option is not always available, it is desirable to have commensurate flow and quality data for the calculations. Where data are not strictly commensurate, it is necessary to make assumptions and accept the additional error component. Because travel time through any reach is probably less than eight hours and the sampling network was normally covered in one day, any effect of diurnal flow variation on quality as inferred from discrete samples was minimized. However, mean daily flow is the smallest unit of flow reported at gaging stations. Also, on a given sample collection day, there was no way to compensate for changes in release rates from reservoirs.

Predictive equations were developed for each reach in a downstream direction beginning with Tahoe-Truckee reach. The gaging site near Truckee, California has not been in operation during the period of this research. Although flow records occasionally show a net loss in this reach the hydrologic model (Butcher, et al., 1970) used to recapitulate tributary inflow does not reconstitute negative gains. Because losses were infrequent (only recorded about 10 percent of the time) and were always less than five percent of the measured flow at the time they occurred, and because recorded losses tended to occur during low flow periods, the assumption of a consistently gaining reach appears sound. Further, extent of water-bearing sediments adjacent to the mainstem is extremely limited which indicates that stream losses to adjacent sediments are minimal. Local and regional ground-water flow systems in volcanic rocks and semi-consolidated materials discharge into Truckee River. During extreme low-flow periods accretions to the river from ground water could be a relatively important component of dispersed flow.

Chemical quality of dispersed flows is calculated from differences between observed outflux of dissolved constituents from a reach and observed influx. In the case of Tahoe-Truckee reach, dispersed flows were recapitulated in terms of monthly volumes. However, dispersed flows on days samples were collected were commonly substantially different from mean monthly dispersed flows. Therefore, flux routing according to mean monthly dispersed flows could introduce a large error into flux-flow or flow-concentration relations derived for the dispersed component.

In an attempt to compensate for noncommensurate quality and flow observations, monthly dispersed flows were decomposed into estimated mean daily dispersed flows. Mean daily dispersed flows on sample collection days were taken to be in the same proportion to monthly dispersed flow as the ratio of mean daily flow to monthly flow observed at Martis Creek, the nearest unregulated, gaged stream to Tahoe-Truckee reach. This assumption recognizes that dispersed inflows to Tahoe-Truckee reach are primarily from ungaged and unregulated streams. For comparative purposes, fluxes of each constituent were routed through the reach according to both mean monthly dispersed flows and estimated mean flows on days samples were collected.

To estimate flows at Truckee gaging site, recapitulated flows were added to recorded flows at Tahoe City according to continuity,

$$Q_D = Q_{Disp} + Q_U \qquad (30)$$

where

Q = flow ($L^3/T$), and

U, Disp, and D = subscripts referring to Tahoe City gage (upstream), dispersed component, and Truckee gage (downstream, respectively.

Flux was calculated for each gaging station as the product of flow and concentration according to the equations:

$$F_U = C_U \cdot Q_U \tag{31}$$

and

$$F_D = C_D \cdot Q_D \cdot \tag{32}$$

According to mass-flux balance, dispersed flux for a reach must be the difference between flux at downstream end and flux at upstream end,

$$F_{Disp} = F_D - F_U \tag{33}$$

Finally, concentrations of dissolved constituents in dispersed flows were estimated by dividing dispersed flux by dispersed flow,

$$C_{Disp} = \frac{F_{Disp}}{Q_{Disp}} \tag{34}$$

Calculations occasionally resulted in negative fluxes and, hence, negative concentrations for all constituents in dispersed flows, whether routed according to mean monthly or estimated daily flows. Because the reach was always gaining ($Q_{Disp}$ is positive) and because concentrations were frequently less at Truckee gaging site than at Tahoe City, negative values of dispersed concentration can be ascribed to errors in recapitulation of dispersed flows and, to a lesser extent, errors in chemical analyses of water samples. In addition, some calculated concentrations were far higher or far lower than values observed in tributaries to the reach. It is probable that the previously mentioned sources of errors are also responsible for these values.

Existence of data which are physically infeasible presents a vexing philosophical problem. If derived data are representative of dispersed flux in Tahoe-Truckee reach, then predictive equations based on these data should predict unrealistic values with the same frequency as observed in the sample. Because of negative concentrations and because the reach was defined to be consistently gaining, such equations could have no physical interpretation. This conflicts with the premise of mass-flux balance for simulation throughout the system. If data are screened, predictive equations can be developed which appear to fit considerations discussed earlier in this section. However, the bias is carried to each point downstream on the mainstem.

In order to be consistent with the premise of flux routing, data were screened prior to development of each predictive equation for Tahoe-Truckee reach. Negative concentrations were rejected. Other improbable values were rejected on a subjective basis which varied between constituents. If concentrations were substantially higher or lower than those recorded for tributaries along the reach, they were rejected. Of 36 observations on each of nine variables, 14.5 percent of those derived from estimated daily flows and 17 percent of those derived from mean monthly flows were rejected.

Concentrations were plotted against dispersed flows on logarithmic coordinates. One scatter diagram was made for each constituent for each method of flux routing. Plots of concentrations versus estimated daily flows showed definite linear relationships for all constituents except Na. Results from routing according to mean monthly flows were not as good. Neither $HCO_3$ nor Na concentrations varied markedly with flow nor were flow-concentration relationships for $SiO_2$, TDS, and remaining anions and cations as strong as in the cases of routing according to estimated daily flows. Table 4 shows correlation coefficients for log-log plots of each constituent versus flows for each method of routing.

## TABLE 4

## CORRELATION COEFFICIENTS FOR DISPERSED FLOW-CONCENTRATION RELATIONSHIPS IN TAHOE-TRUCKEE REACH

| Constituent | Flux Routing by estimated daily flows | Flux Routing by mean monthly flows |
|---|---|---|
| $HCO_3$ | -.60 | -.15 |
| Cl | -.64 | -.43 |
| $SO_4$ | -.68 | -.48 |
| Na | -.32 | -.21 |
| K | -.51 | -.76 |
| Ca | -.73 | -.44 |
| Mg | -.80 | -.69 |
| $SiO_2$ | -.66 | -.53 |
| TDS | -.87 | -.53 |

Equations of the form

$$C_{Disp} = a\, Q_{Disp}^{-b}$$

were derived by fitting least squares lines to the log transmitted data. As an example, Figure 7 shows the plotted data and regression line for TDS. Residuals were analyzed graphically and statistically for systematic time-dependent behavior in the same manner as discussed in previous sections. Behavior of residuals appeared to be random with respect to time. Therefore, predictive equations adopted were simply the exponential relationships describing the regression lines.

R.L. Bateman (Ph.D. dissertation, in preparation) developed flow-concentration regression equations of the exponential type for the five principle ungaged tributaries along Tahoe-Truckee reach. Regressions were based on 12 pairs of flow and quality observations made under conditions ranging from minimum to peak flows over a two year period. For each constituent, regression coefficients (exponents) vary by a factor of approximately three among the five streams. Regression coefficients for dispersed relationships lie within, or very close to, the range of values for tributaries as shown in Table 5.

The ordinate intercept (a) for each dispersed flow-concentration relationship is generally greater than any calculated for the same constituent in the five individual tributaries. The exceptions, $HCO_3$ and Na are within 0.2 and 10 percent, respectively, of maximums among the tributaries. If conditions prescribed for Equation (19) are approximately correct in Tahoe-Truckee reach, then the unsampled component of dispersed flow must be more mineralized than any of the five tributaries. Development of Equation (19) required the assumption of proportional tributary inflows. If this hypothesis is valid, then (except for $SO_4$) variation in regression coefficients (Table 5) for each constituent is sufficiently small that application of Equation (19) for dispersed flow-concentration relationships can be closely approximated by the general relation

$$C = aQ^{-b}$$

for flows ranging over three orders of magnitude. The previously mentioned similarities between hydrographs of gaged unregulated tributaries in the vicinity of Lake Tahoe plus similarities in size, slope, and aspect of tributary basins lend credence to the hypothesis of proportional flows. Therefore, the exponential predictive equations developed for Tahoe-Truckee reach appear to conform to conditions postulated for a consistently gaining reach whose sources of dispersed flow are primarily tributaries.

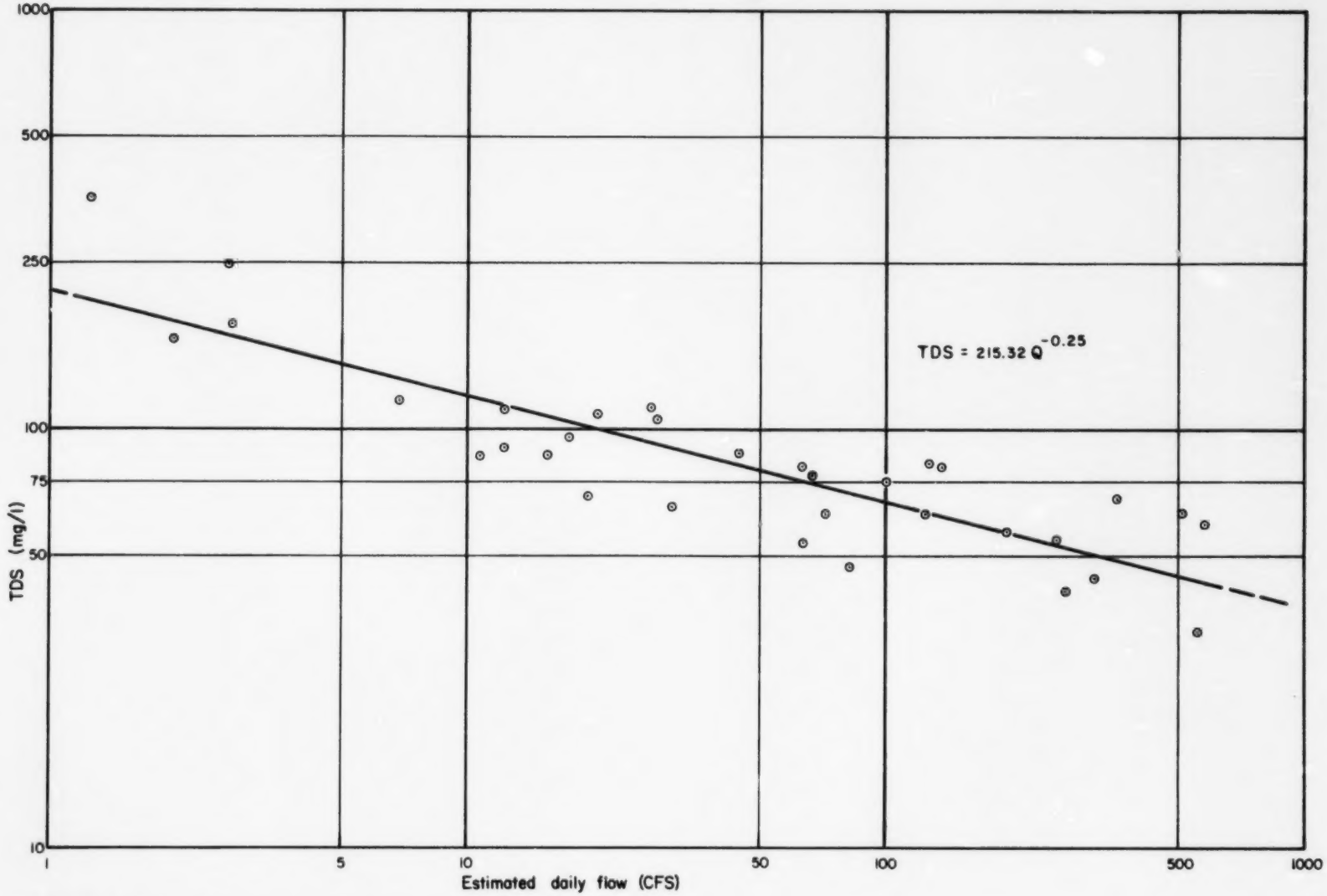


**FIGURE 7. TDS-Flow Relation for Dispersed Input in Tahoe-Truckee Reach.**

## TABLE 5

## COMPARISON BETWEEN ORDINATE INTERCEPTS (a) AND REGRESSION COEFFICIENTS (b) FOR DISPERSED FLOW-CONCENTRATION EQUATIONS AND THOSE DERIVED FOR PRINCIPAL TRIBUTARIES TO TAHOE-TRUCKEE REACH

| | Range for 5 Tributaries | | Tahoe-Truckee Reach | |
|---|---|---|---|---|
| Constituent | a | b | a | b |
| $HCO_3$ | 45.60 to 73.11 | 0.11 to 0.30 | 72.98 | 0.13 |
| Cl | 0.33 to 3.80 | 0.08 to 0.55 | 22.08 | 0.46 |
| $SO_4$ | 0.47 to 47.42 | -0.21 to 0.55 | 65.27 | 0.50 |
| Na | 3.68 to 7.48 | 0.14 to 0.34 | 6.72 | 0.09 |
| K | 0.66 to 2.62 | 0.08 to 0.28 | 2.81 | 0.23 |
| Ca | 7.35 to 27.90 | 0.11 to 0.35 | 28.69 | 0.25 |
| Mg | 2.53 to 5.86 | 0.14 to 0.33 | 11.94 | 0.34 |
| $SiO_2$ | 9.98 to 29.24 | 0.01 to 0.21 | 51.98 | 0.22 |
| TDS | 64.70 to 147.20 | 0.12 to 0.33 | 215.34 | 0.25 |

In Truckee-Farad reach, as in Tahoe-Truckee reach, data for predictive equations were developed from differences between measured inflows and outflows. In this reach gaged inflow consisted of Martis Creek and Prosser and Boca Reservoirs. As discussed earlier, Donner Creek flows were taken as the sum of estimated Cold Creek flows and gaged releases from Donner Lake. Also considered to be measured inflow were the recapitulated flows at defunct Truckee gage. Outflow was measured at Farad gage near the California-Nevada state line. Water-quality data was based on samples collected at each of the gaging sites with the exception of Donner Creek. Quality data used for Donner Creek were based on water samples collected above the confluence with Truckee River.

Budgeting of both mean monthly and estimated daily flows through Truckee-Farad reach shows occasional losses which appear to be associated with low flow conditions. The presence of springs adjacent to the river, the presence of a flowing well adjacent to the river in the vicinity of Prosser Creek, and the general discharge of regional and local ground-water systems to Truckee River seem to contradict the possibility of consistent losses to ground water along the reach. Most of the apparent losses are probably due to inaccurate recapitulation of flows in Tahoe-Truckee reach and Cold Creek.

Dispersed fluxes, concentrations, and flows were calculated on the basis of budgeting both mean monthly and estimated daily flows. Calculations from estimated daily flows and concentrations from 39 water sample analyses showed net flow losses in the reach on 13 days and an average of six negative concentrations per constituent. By comparison, results from monthly budgeting showed net flow losses nine times and an average of three negative concentrations per constituent. Results from budgeting mean monthly flows appeared more plausible than results from daily budgeting. Therefore, mean monthly flows were used to develop predictive equations for quality of dispersed flows.

Because losses were indicated 23 percent of the time, two predictive techniques were developed. In one case, negative values were disregarded and least square lines were fit through plots of logarithms of concentrations versus logarithms of dispersed flows. Residuals were tested graphically and statistically for systematic time dependent behavior using methods discussed in previous sections. Because time-systematic behavior was not discernible, predictive equations for this case had tne usual exponential form. Figure 8 shows a plot of TDS concentrations and mean monthly flows on logarithmic coordinates with the least squares regression line.

As an alternative, net fluxes for each constituent were plotted versus net flows. All data for both methods of budgeting were considered and a fourth order polynomial was fit by curvilinear regression to each plot. Data calculated from estimated daily flow budgets has less scatter than those based on budgets of mean monthly flows. Figure 9 shows the plot and regression line for dispersed TDS flux versus dispersed flow. Deviations from polynomial regression lines appeared to be random.

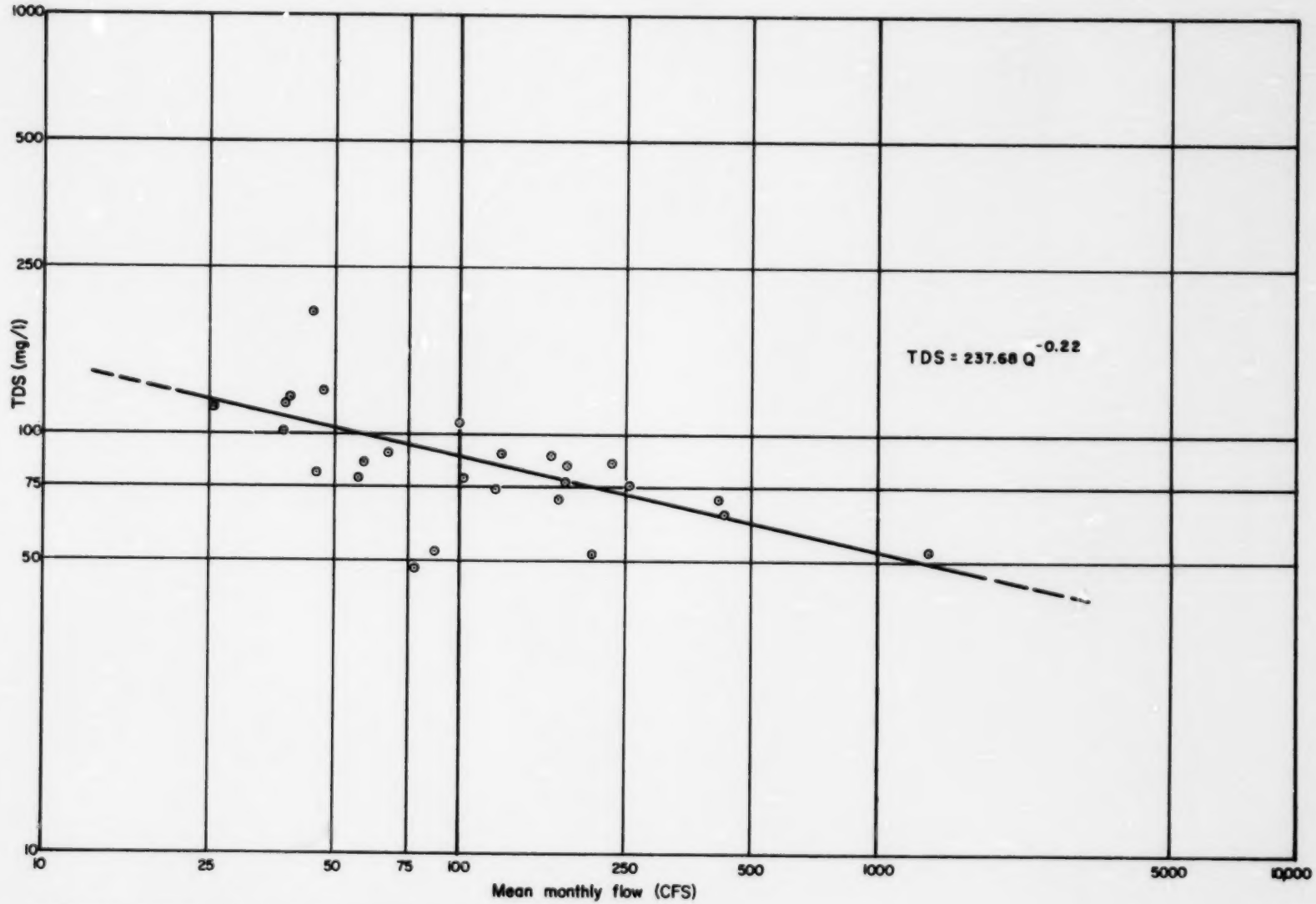


**FIGURE 8. TDS-Flow Relation for Dispersed Input in Truckee-Farad Reach.**

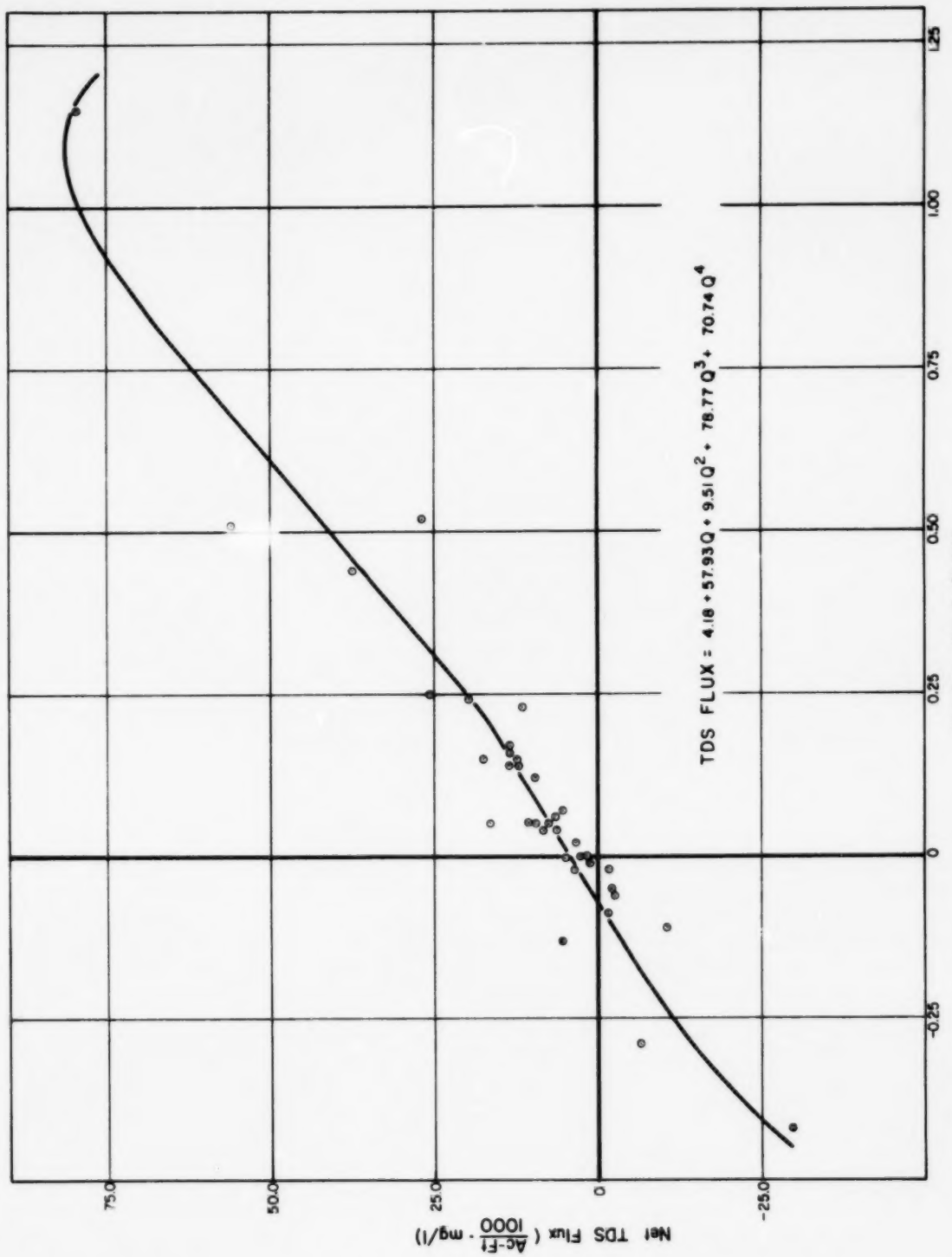


FIGURE 9. Net TDS Flux Versus Net Flow in Truckee-Farad Reach.

The fourth order polynomials explained more of the variance in flux-flow relationships than did exponential equations in the case of flow-concentration relationships. Table 6 lists correlation coefficients for each method of prediction for each constituent. However, correlation coefficients are not directly comparable in terms of predictive capabilities of the two methods because data are presented differently (flow-concentration vs flux-flow). To determine which predictive method was more reliable, a prototype model was operated using each method. Comparisons were made on the basis of recapitulation of observed concentrations at Farad.

**TABLE 6**

**CORRELATION COEFFICIENTS FOR DISPERSED FLUX-FLOW AND FLOW-CONCENTRATION RELATIONS IN TRUCKEE-FARAD REACH**

| Constituent | 4th Order Polynomial for Flux-Flow Relationship | Flow-Concentration Relationship $C = aQ^{-b}$ |
|---|---|---|
| $HCO_3$ | 0.30 | -0.68 |
| Cl | 0.46 | -0.42 |
| $SO_4$ | 0.67 | -0.38 |
| Na | 0.83 | -0.68 |
| K | 0.79 | -0.57 |
| Ca | 0.95 | -0.78 |
| Mg | 0.88 | -0.27 |
| $SiO_2$ | 0.89 | -0.32 |
| TDS | 0.96 | -0.58 |

**TABLE 7**

**CORRELATION COEFFICIENTS FOR ESTIMATED VERSUS OBSERVED CONCENTRATIONS IN TRUCKEE RIVER AT FARAD USING DISPERSED FLOW-CONCENTRATION AND FLUX-FLOW PREDICTIVE TECHNIQUES FOR TRUCKEE-FARAD REACH**

| Constituent | Flow-Concentration Relationships | Flux-Flow Relationships |
|---|---|---|
| $HCO_3$ | -0.76 | 0.62 |
| Cl | -0.48 | 0.53 |
| $SO_4$ | -0.41 | 0.41 |
| Na | -0.78 | 0.75 |
| K | -0.68 | 0.62 |
| Ca | -0.75 | 0.75 |
| Mg | -0.39 | 0.31 |
| $SiO_2$ | -0.25 | 0.49 |
| TDS | -0.80 | 0.73 |

Table 7 shows correlation coefficients for estimated versus observed concentrations of dissolved constituents in Truckee River at Farad according to the method of estimating chemical quality of dispersed flows entering Truckee-Farad reach. Except for Cl and $SiO_2$, exponential flow-concentration relations appear slightly more

effective than flux-flow relations for recapitulating concentrations in the mainstem. Consequently, exponential flow-concentration relations selected as predictors for chemical quality of dispersed flows in Truckee-Farad reach.

As in Tahoe-Truckee reach, Bateman (Ph.D. dissertation, in preparation) developed exponential flow-concentration regression equations for four principal ungaged tributaries along Truckee-Farad reach. Regressions were based on 12 pairs of flow and quality observations under conditions of flow ranging from minimum to near peak over a two year period. Table 8 shows ranges of values of ordinate intercepts and regression coefficients developed for tributaries and ordinate intercepts and regression coefficients developed for dispersed flows. Comparisons between observed flow-concentration relationships and dispersed relationships are not definitive. It is doubtful that an assumption of proportional tributary hydrographs is valid because of marked differences in mean basin elevation and dissimilarities in size and aspect. However, the degree to which the assumption may be violated is unknown. The tendency for dispersed ordinate intercepts to be higher than those for individual tributaries is probably caused by ground-water inflow along the reach.

**TABLE 8**

**COMPARISON BETWEEN ORDINATE INTERCEPTS (a) AND REGRESSION COEFFICIENTS (b) FOR DISPERSED FLOW-CONCENTRATION EQUATIONS AND THOSE DERIVED FOR PRINCIPAL TRIBUTARIES TO TRUCKEE-FARAD REACH**

| | Range for 4 Tributaries | | Truckee-Farad Reach | |
|---|---|---|---|---|
| Constituent | a | b | a | b |
| $HCO_3$ | 62.23 to 109.40 | 0.11 to 0.26 | 213.40 | 0.28 |
| Cl | 0.34 to 1.40 | -0.29 to 0.37 | 10.59 | 0.25 |
| $SO_4$ | 0.46 to 39.08 | 0.27 to 0.46 | 26.66 | 0.34 |
| Na | 4.47 to 7.18 | 0.11 to 0.20 | 53.58 | 0.45 |
| K | 1.12 to 2.22 | 0.00 to 0.31 | 6.19 | 0.31 |
| Ca | 8.90 to 28.30 | 0.14 to 0.21 | 57.91 | 0.33 |
| Mg | 4.10 to 6.76 | 0.15 to 0.29 | 4.22 | 0.07 |
| $SiO_2$ | 24.21 to 40.36 | 0.00 to 0.09 | 49.03 | 0.18 |
| TDS | 85.90 to 183.70 | 0.13 to 0.22 | 237.68 | 0.22 |

Hydrology of Truckee Meadows is very complex. It is the site of both Reno-Sparks urban area and considerable agricultural development. Water is diverted from Truckee River in as many as 19 locations for agricultural and municipal uses both above and below Reno gage. Tributaries are periodically diverted for domestic and agricultural use. Ground water is pumped for the same purposes. Return flows include mineralized waters from hot springs and large areas undergoing oxidation of disseminated pyrite, treated sewage effluent, agricultural return flows, and runoff from tributaries. The relationship between flow in Truckee River and ground water in contiguous aquifers is not quantitatively understood. However, it appears that Truckee Meadows reach is both gaining from and losing to contiguous aquifers with respect to both time and location in the reach (Cohen and Loeltz, 1964; Cooley, Fordham, and Westphal, 1972).

Because of the complex hydrology, attempts were made to decompose Truckee Meadows reach into smaller components through which it might be possible to characterize effect of individual factors or groups of factors on chemical quality of water. Dispersed data were calculated for Farad to Reno gage, Reno gage to Vista, and the entire Truckee Meadows (Farad to Vista) reach. Flux and flow budgets were based on mean daily flows on days in which water samples were collected. Dispersed flow-concentration relations were too poor to be used for reliable predictive relationships in any of the three reaches.

Steamboat Creek and North Truckee drain carry the preponderance of return flows from Truckee Meadows to Truckee River. Although concentrations of dissolved constituents in these streams show definite annual cyclical behavior, flows are not gaged in the vicinity of the confluences with Truckee River. Concurrent flow and quality measurements conducted as part of this research show that quality is not related to flow rates in these streams. Therefore, it was not possible to recapitulate flows on the basis of quality records. Attempts to utilize flows as recapitulated by Cooley et al. for budgeting fluxes in these streams also proved unsuccessful.

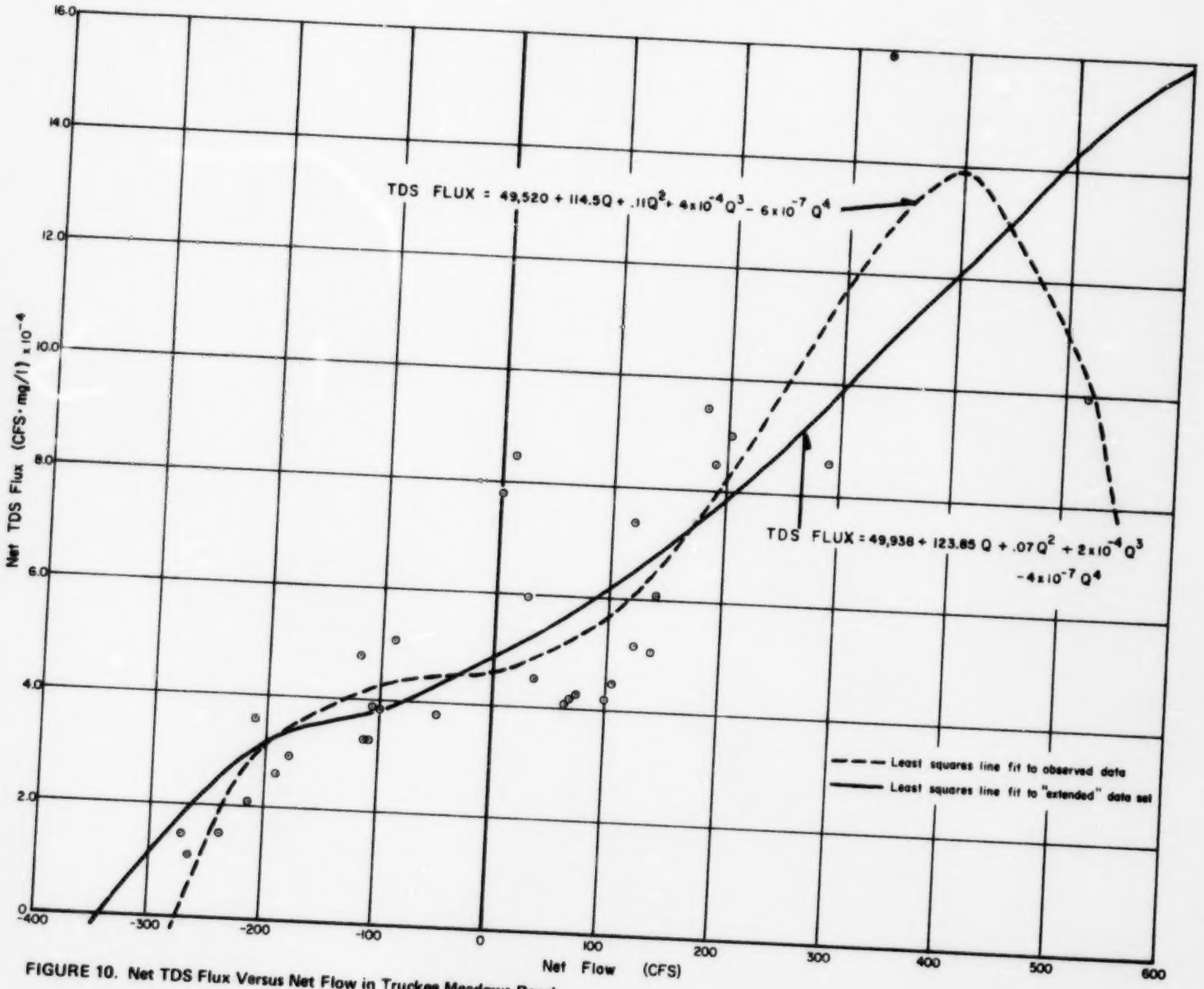


FIGURE 10. Net TDS Flux Versus Net Flow in Truckee Meadows Reach.

Plots of net flux versus net flow showed some promise, particularly when Truckee Meadows reach was considered in its entirety. Figure 10 shows dispersed TDS flux plotted against dispersed flow. Regression analyses were performed on each data set for straight lines and polynomials up to the fourth order, the latter being arbitrarily set as the maximum order for representation of the general data configuration. Results showed that fourth order polynomials explained the highest percentage of variance. The dashed line on Figure 10 is a least squares fourth order polynomial fit to the observed data. Historically, both net gains and net losses of flow in Truckee Meadows reach have been larger. Therefore, use of the equation for this line for predictive purposes must be restricted to the range of actual observations.

To allow for extrapolation beyond observed data, a pair of flux and flow data was estimated for each extreme on the basis of historical dispersed flows and the apparent trend of plotted data. A least squares fourth order polynomial was fit to the extended data set as shown by the solid line on Figure 10. This simplified computer programming by eliminating the necessity for additional equations when extrapolations are required. Table 9 shows correlation coefficients for each predictive equation according to the constituent involved.

**TABLE 9**

**CORRELATION COEFFICIENTS FOR 4TH ORDER POLYNOMIAL FITS TO "EXTENDED" DISPERSED FLUX-FLOW DATA IN TRUCKEE MEADOWS REACH**

| Constituent | Correlation Coefficient |
|---|---|
| $HCO_3$ | 0.83 |
| Cl | 0.85 |
| $SO_4$ | 0.80 |
| Na | 0.80 |
| K | 0.84 |
| Ca | 0.91 |
| Mg | 0.86 |
| $SiO_2$ | 0.82 |
| TDS | 0.87 |

Major degradation of chemical quality of Truckee River often occurs between Reno gage and Vista. For this reason it is desirable to simulate concentrations at Reno gage. Because it was not possible to apply the flux-balance concept in the Farad to Reno reach, linear regression equations were developed to describe relationships between concentrations of individual ionic constituents at Reno and those at Farad. This method was chosen over flow-concentration relationships at Reno gage because it forces concentrations at Reno to respond in the same direction as those at Farad. In this manner, simulated concentrations at Reno are more likely to be comparable with commensurate simulated concentrations at Farad and Vista.

Vista-Derby Dam reach is in the upstream part of Truckee Canyon. When they occur, gains along the reach are from ephemeral tributaries, returns from Tracy power plant, and ground water. Losses include diversions for agriculture adjacent to the river, diversions for Tracy power plant, and seepage losses. At Derby Dam at the lower end of the reach, Truckee River flows are diverted to Carson River drainage via Truckee Canal. These diversions, which take place above the gaging station on the mainstem, have ranged from zero during winter months to more than 80 percent of Truckee River flow as measured at Vista gage during summer months.

Calculation of dispersed fluxes and flows was similar to other reaches. Outflow from the reach was considered to be the sum of flows measured at Truckee River below Derby Dam and Truckee Canal near Derby Dam. Flux from this reach was calculated as the product of outflow and concentration of dissolved constituents observed in flows past the gaging site on the mainstem. As in Truckee Meadows, flow-concentration relations were poor and had little predictive value because of scatter and large percentage of negative gains. Flux-flow relationships were also poorly defined as indicated by the plots of dispersed TDS flux versus dispersed flow shown in Figure 11. Again, extremal values of flux and flow were selected subjectively on the basis of recorded extremes of dispersed flow (which were larger than those observed during this research) and extrapolation of observed quality data. Predictive equations were those for least squares fourth order polynomials fit to the extended data sets.

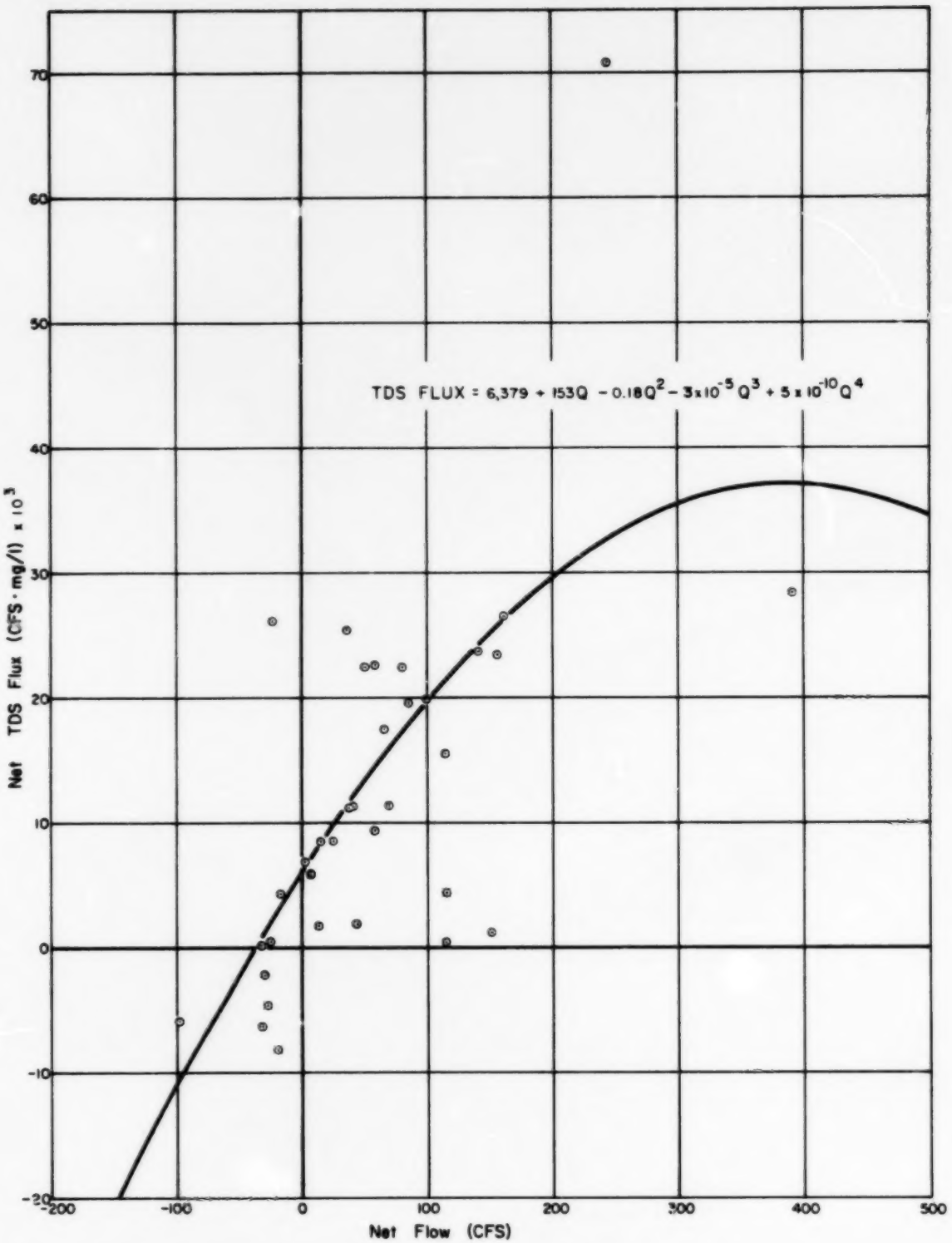


FIGURE 11. Net TDS Flux Versus Net Flow in Vista-Derby Dam Reach.

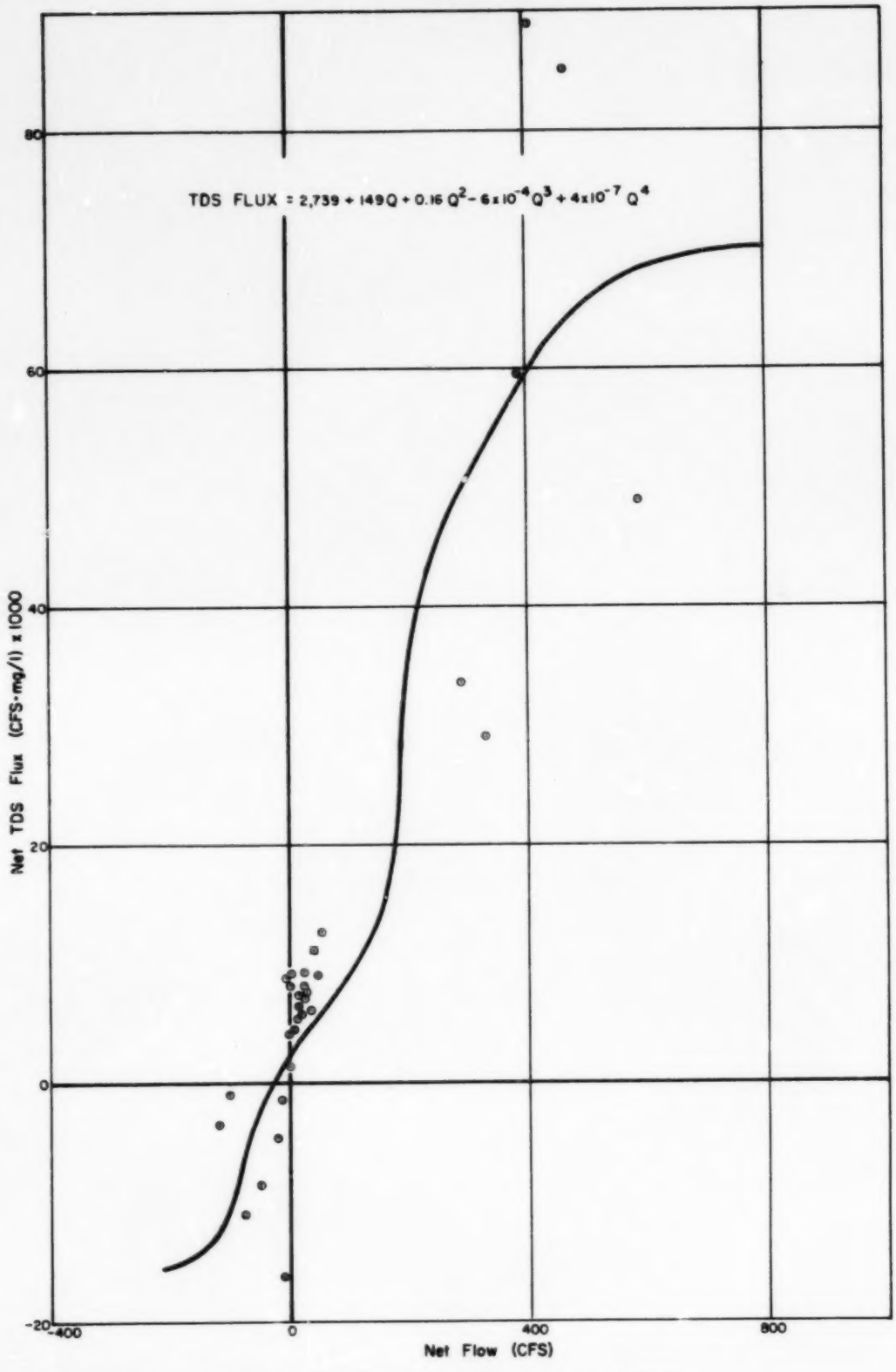


FIGURE 12. Net TDS Flux Versus Net Flow in Derby Dam-Wadsworth Reach.

Derby Dam-Wadsworth reach is in the downstream part of Truckee Canyon. As mentioned previously, management practices in Truckee Canal complicate flux budgeting through this reach. Two wasteways on the canal are often used for regulation of flows by returning water to the river downstream from both river and canal gaging stations. Other gains along the reach are from ephemeral streams and ground water. Losses are due to seepage to ground water and diversions for agriculture adjacent to the river.

Calculations of dispersed flows and fluxes were based on observations on the mainstem. Attempts to budget fluxes through the canal failed because flow measurements on the canal near Derby Dam and those at the U.S.G.S. site below the wasteways occasionally showed a net gain in the intervening reach. Field reconnaissance shows that gains in the canal are highly unlikely if not impossible. Again, lack of well-defined flow-concentration relationships and frequent negative gains made the exponential form of predictive equation infeasible for the dispersed component. Flux-flow relationships are reasonably well defined for gains higher than about 60 cfs. Regression analyses showed fourth order polynomials explained the largest percentage of the variance in flux-flow data. Extreme values of flux and flow were estimated and fourth order polynomials were fit to the extended data sets. Figure 12 shows flux-flow data and the line whose equation was used for predictions of TDS fluxes.

Like other lower river reaches, diversions for agriculture adjacent to the river and seepage to adjacent aquifers occur along Wadsworth-Nixon reach. Although some accretions are due to flows in ephemeral tributaries, most are due to ground water. Net losses, when they occur, are usually associated with high flows (in excess of 900 cfs as measured at Wadsworth gage) which may be accompanied by overbank flooding. Except in the case of $SiO_2$, net depletion of dissolved constituents can probably be attributed to a combination of flow measurement errors and analytical uncertainties.

As shown in Figure 13, flux-flow relationships are reasonably good for net gains along the reach but are nonexistent for net losses. Through curvilinear regression, it was possible to explain from 7 to 66 percent of the variance in flux-flow data for the various constituents. When losses through the reach are disregarded, all constituents show strong flow-concentration relationships of the exponential form. Figure 14 shows a plot of dispersed TDS concentrations and flow plotted on logarithmic coordinates with the least squares line. From visual inspection of the chemical data, it is estimated that concentrations at either end of the reach are within 10 percent of each other on the average. Because of the poor flux-flow relationship in the range of negative flows, the exponential form of predictor equation was used for each constituent. For periods of net flow loss, concentrations at Nixon were set equal to those at Wadsworth.

## STOCHASTIC COMPONENT

In previous sections, methods for estimating water-quality parameters were discussed. Accuracy was measured in terms of percentage of variance in quality parameters explained by predictor variables. Degree of accuracy varied according to flow component (dispersed, tributary, impoundment) and to constituent involved. In simulation it is necessary to preserve the statistical properties of the sample upon which predictive equations are based. This requires that an error component be added to the deterministic part of the predictive equation to account for unexplained variance. The general equation used for simulation can be expressed as

$$Y_i = D_i + E_i \tag{35}$$

where

$Y_i$ = estimated parameter,
$D_i$ = deterministic component of the estimate,
$E_i$ = error component due to unexplained variance, and
$i$ = sequential estimate (from 1 to n simulated values per equation).

If $E_i$ is a random deviate whose parent population is normally distributed about a zero mean, then it can be estimated according to the relationship

$$E_i = t_i S_E \tag{36}$$

where

$t_i$ = random number from population with zero mean and unit variance, and
$S_E$ = estimated standard deviation of population of $E_i$'s.

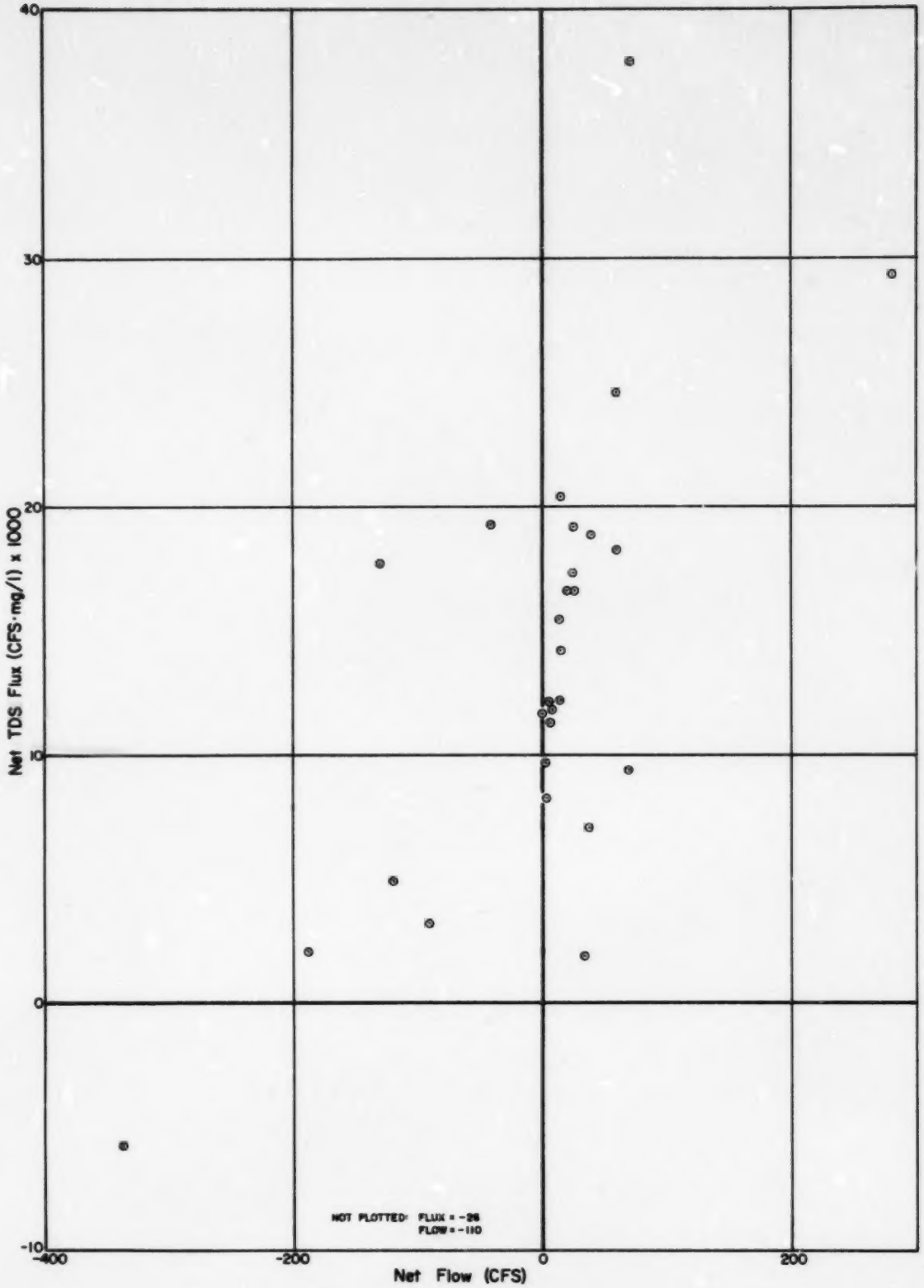


**FIGURE 13. Net TDS Flux Versus Net Flow in Wadsworth-Nixon Reach.**

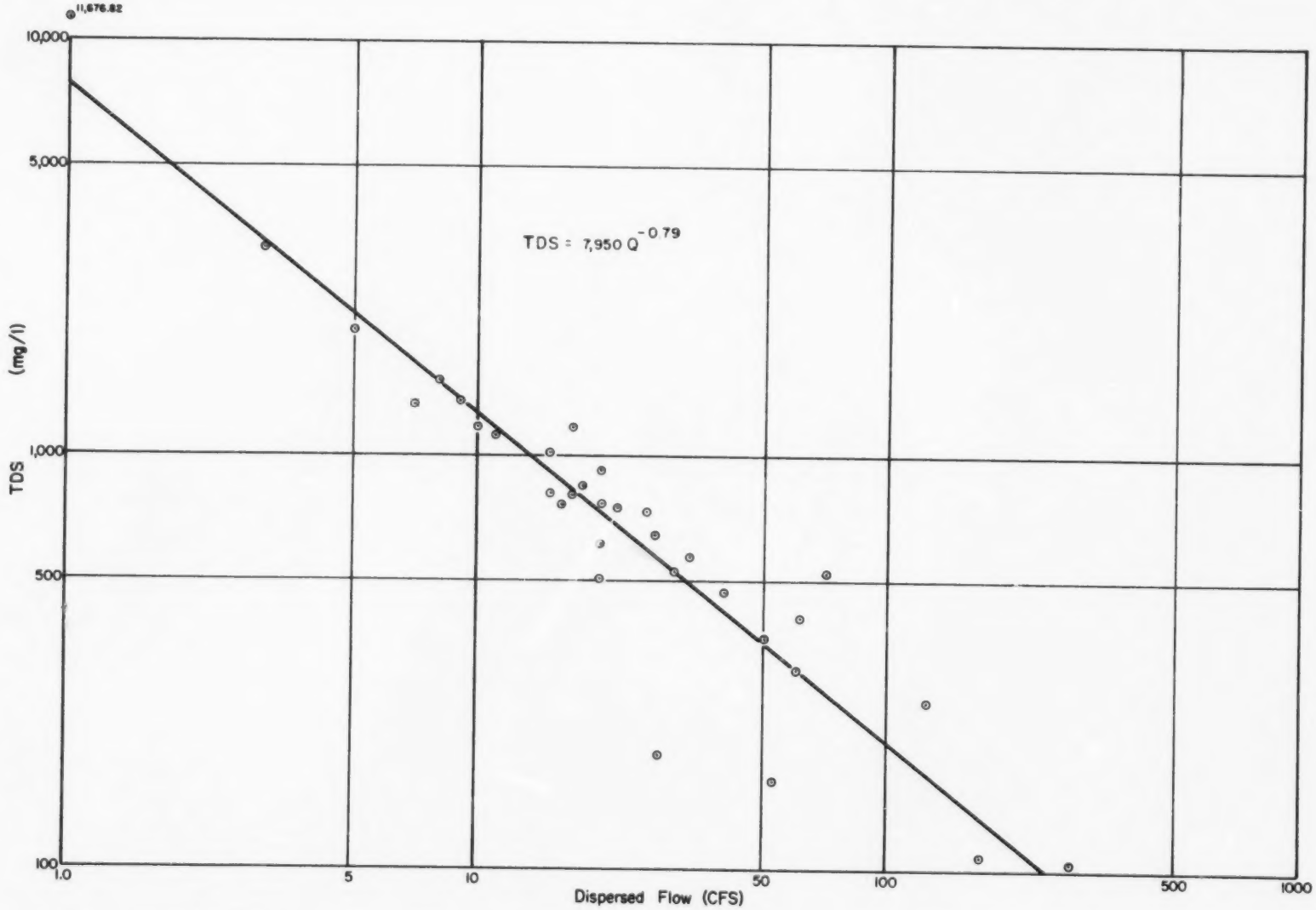


**FIGURE 14. TDS-Flow Relation for Dispersed Input in Wadsworth-Nixon Reach.**

The product of the coefficient of determination (correlation coefficient squared, $r^2$) and the estimated variance of the population of dependent variables ($S_E^2$) equals the percentage of variance explained by the deterministic part of the equation. Unexplained variance ($S_E^2$) is the product of the coefficient of nondetermination ($1-r^2$) and estimated variance of the population of dependent variables. Therefore, an alternative expression for the random deviate is

$$E_i = t_i S_Y \cdot \sqrt{1-r^2} \tag{37}$$

To eliminate the necessity for statistically evaluating residuals, this feature was programmed into the model as an option.

To check hypotheses of random behavior, normal distributions, and zero means, deviations of estimates from observed values (residuals) for each predictive equation were examined visually. For selected locations along the reaches above Farad and at Reno gage, residuals were also tested for normal distributions according to the Chi squared ($\chi^2$) criterion of Steel and Torrie (1960).

Where all available data were used for formulation of predictive equations, residuals had normal or near-normal distributions for all constituents except Cl and $SO_4$. Residuals showed random behavior about mean values near zero in all of the above cases. As expected, where data were screened prior to use in formulation of predictive equations and where estimated extremes were added to basic data sets, statistical distributions were less well defined. However, except in Derby Dam-Wadsworth reach, residual behavior appeared to be random. In all cases, mean residuals were not statistically different from zero as determined by the statistic "t" at the five percent level of significance. The suggestion of nonrandom behavior for $HCO_3$, Cl, $SO_4$, Na, and TDS fluxes in Derby Dam-Wadsworth reach was caused by the estimates of extremel flux-flow values.

In some cases, frequency histograms for residuals were multi-modal or skewed. Selected skewed distributions were transformed and tested for lognormality according to the previously mentioned $\chi^2$ criterion with negative results. Most skewed distributions were caused by one or two observations at one tail of a histogram. Because their occurrences were not systematic with respect to constituent or type of predictive equation, skewed data sets were not tested for gamma distributions. It is probable that the central limit theorem applies and normal distributions are approached as sample size increases.

In this model, Equation 36 was used to estimate error terms, $E_i$. Values of $S_E$ were those derived from the analysis of residuals mentioned above. Values of $t_i$ were calculated within the model. According to Fiering and Jackson (1971), if 12 random numbers in the range 0 to 1 from a uniform distribution are summed, random numbers from a population with zero mean and unit variance can be closely approximated by the transformation

$$t_i = \sum_{j=1}^{12} a_j \cdot 6 \tag{38}$$

where

$a_j$ = uniformly distributed random number, and the value 6 is substracted to preserve a zero mean.

An intrinsic function (RANF) of the CDC 6400 computer was used to generate uniformly distributed random numbers ($a_j$) in the range of 0 to 1 for use in Equation 38.

## SECTION V

## MODEL STRUCTURE

The model was programmed in FORTRAN 4 language for the CDC 6400 computer. It consists of a main program, TRIV, and four subprograms, UPRIV, TMEADWS, LORIV, and GAUSS. Predictor variables, predictive equations and, in the verification mode, observed water-quality data are read as input to TRIV and results of calculations are printed as output from TRIV. Subprograms UPRIV, TMEADSW, and LORIV are used to estimate quality parameters and to budget flows in river segments between Tahoe City and Farad, Farad and Vista, and Vista and Nixon, respectively. These subprograms are called separately from the main program. Subprogram GAUSS is used to generate random numbers and is called from other subprograms each time the deterministic part of an estimate of a water-quality parameter has been completed. Figure 15 is a schematic showing the relationship between main program and subprograms and outlines of their functions. To understand how the model works, it is convenient to consider the main program and each subprogram separately and in detail.

In the model, all operations are performed for one constituent at a time for the entire length of record, including printing of results. For this reason it is convenient to consider TRIV in two segments. Only one pass is made through the first segment. Data read and manipulated in this segment are reused for each constituent. The second segment is in a loop and re-referenced each time it becomes necessary to consider a different constituent. Operations performed in this segment are peculiar to a particular constituent. The program automatically defaults to completion when the control card denoting end of file is encountered. Figure 16 is a flow diagram showing sequence of operations in TRIV.

The sequence of operations in the initial segment of TRIV is listed below:

1. Read the number of months (NOMOS) for which simulations are to be made.
2. Read recorded flows ($V_{ij}$ : i = 1, 2, ... NOMOS : j = location designation) as thousands of acre feet per month. Set flows to zero at all other stations.
3. Read time labels ($YR_1$; $MO_i$, i = 1, 2, ..., 12) for identification of model output. Assign a length of time in days to each month.
4. Calculate mean daily flows in cfs ($Q_{ij}$) for each station where flows are recorded.
5. Read predictor variables ($TVAR_{ijk}$ : i = 1, 2, ..., NOMOS; j = variable identifier; k = equation identifier) for reservoir equations. There are two equations for Boca Reservoir because of the observable change in regimen after Stampede Reservoir became operational upstream.

The sequence of operations in the second segment is listed below:

1. Read the name of the constituent for which flux and concentration calculations will be performed. If the card marking the end of the data deck (end of file card) is encountered, the program defaults to termination.
2. Read beginning concentrations for releases from Donner Lake (DCON), Boca Reservoir (BEGCON), Prosser Reservoir (PCON) and the adjustment factor (AVG) for predicted concentrations in Donner Creek near the confluence with Truckee River.
3. Read regression parameters for simple and exponential regression equations. $YS_i$ is an ordinate intercept and $BS_i$ is the corresponding regression coefficient where the subscript "i" denotes the station.
4. Read regression parameters for multiple regression equations. $OICPT_j$ is an ordinate intercept and $BM_{ij}$ are the corresponding partial regression coefficients. "j" denotes the station and i refers to a particular predictor variable.
5. Set predictor variables for reservoirs into a "working" array ($VAR_{ijk} = TVAR_{ijk}$).
6. Read average monthly concentrations in Truckee River near Tahoe City and average monthly residuals for Martis Creek and Donner Creek as $R_{ij}$ where i = 1, 2, ..., 12 and j denotes the station. If for a particular constituent cyclical tendencies are absent, zero values or, in the case of Truckee River near Tahoe City, average of all observations are read.
7. Read concentrations observed in flows below Donner Lake and Boca Reservoir (TILT1, TILT2) when flow rates are less than 1.5 cfs and 0.5 cfs, respectively.
8. Read regression parameters for flow-concentration relations in Prosser Creek above Prosser Reservoir and Little Truckee River above Boca Reservoir. $OR_i$ is the ordinate intercept, $BR_i$ is the regression coefficient, and the subscript denotes the location.

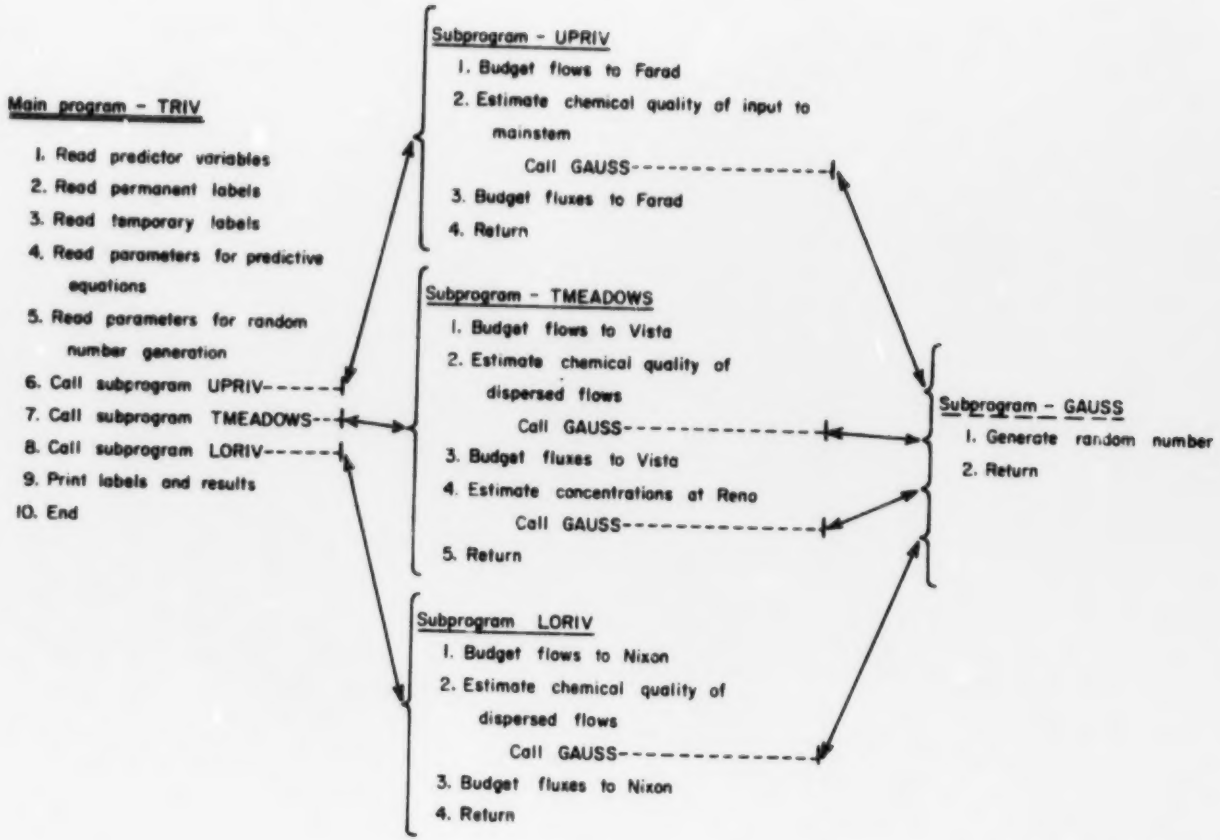
Main program - TRIV
1. Read predictor variables
2. Read permanent labels
3. Read temporary labels
4. Read parameters for predictive equations
5. Read parameters for random number generation
6. Call subprogram UPRIV
7. Call subprogram TMEADOWS
8. Call subprogram LORIV
9. Print labels and results
10. End
Subprogram - UPRIV
1. Budget flows to Farad
2. Estimate chemical quality of input to mainstem
Call GAUSS
3. Budget fluxes to Farad
4. Return
Subprogram - TMEADOWS
1. Budget flows to Vista
2. Estimate chemical quality of dispersed flows
Call GAUSS
3. Budget fluxes to Vista
4. Estimate concentrations at Reno
Call GAUSS
5. Return
Subprogram LORIV
1. Budget flows to Nixon
2. Estimate chemical quality of dispersed flows
Call GAUSS
3. Budget fluxes to Nixon
4. Return
Subprogram - GAUSS
1. Generate random number
2. Return

FIGURE 15. Schematic of Tahoe-Truckee Inorganic Water-Quality Model.

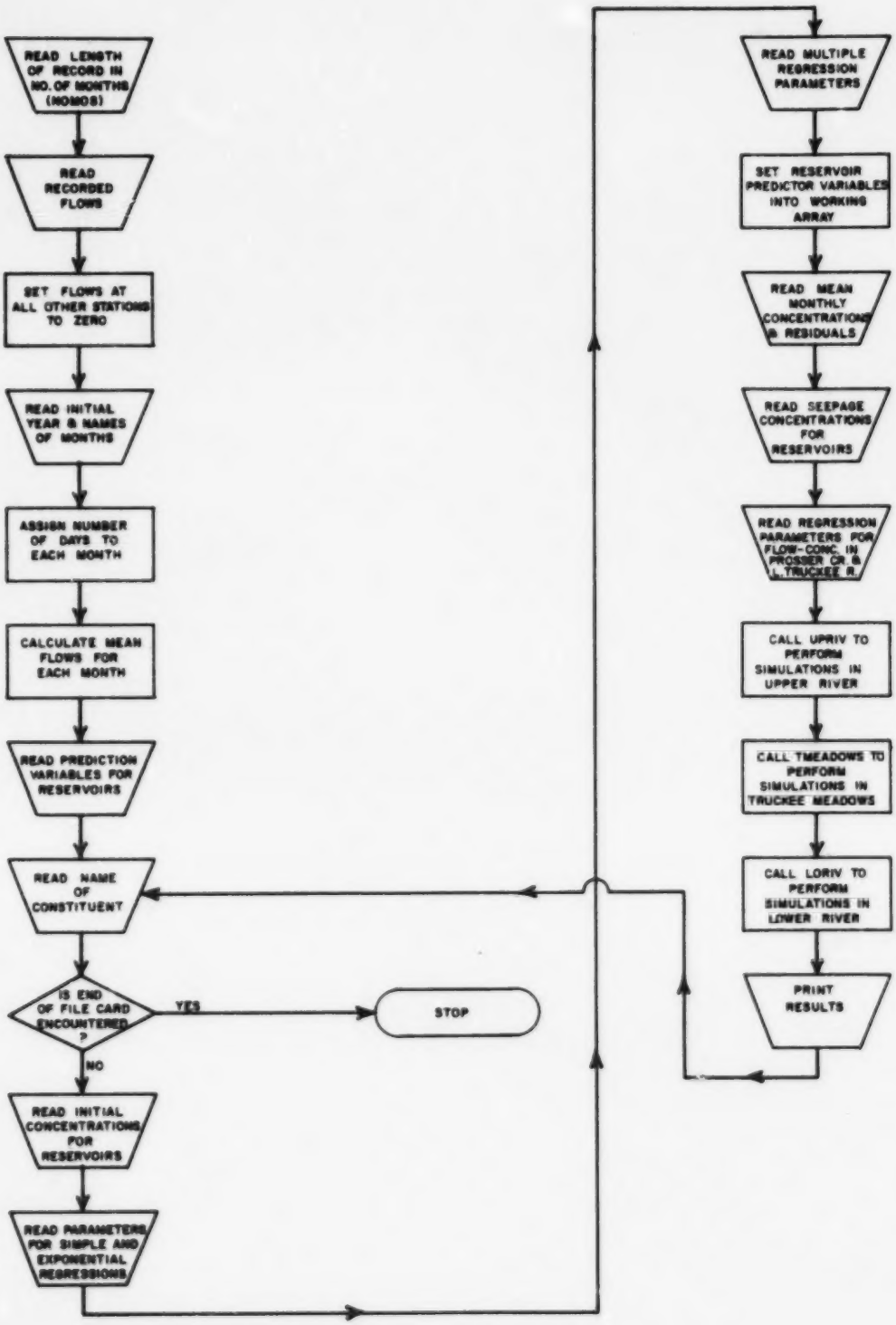
READ LENGTH OF RECORD IN NO. OF MONTHS (NOMOS)
READ RECORDED FLOWS
SET FLOWS AT ALL OTHER STATIONS TO ZERO
READ INITIAL YEAR & NAMES OF MONTHS
ASSIGN NUMBER OF DAYS TO EACH MONTH
CALCULATE MEAN FLOWS FOR EACH MONTH
READ PREDICTION VARIABLES FOR RESERVOIRS
READ NAME OF CONSTITUENT
IS END OF FILE CARD ENCOUNTERED ?
YES
STOP
NO
READ INITIAL CONCENTRATIONS FOR RESERVOIRS
READ PARAMETERS FOR SIMPLE AND EXPONENTIAL REGRESSIONS
READ MULTIPLE REGRESSION PARAMETERS
SET RESERVOIR PREDICTOR VARIABLES INTO WORKING ARRAY
READ MEAN MONTHLY CONCENTRATIONS & RESIDUALS
READ SEEPAGE CONCENTRATIONS FOR RESERVOIRS
READ REGRESSION PARAMETERS FOR FLOW-CONC IN PROSSER CR & L. TRUCKEE R.
CALL UPRIV TO PERFORM SIMULATIONS IN UPPER RIVER
CALL TMEADOWS TO PERFORM SIMULATIONS IN TRUCKEE MEADOWS
CALL LORIV TO PERFORM SIMULATIONS IN LOWER RIVER
PRINT RESULTS

**FIGURE 16. Flow Diagram for Main Program (TRIV).**

9. Read parameters for random number generation. $CND_i$ is a correlation coefficient from regression and $SD_i$ is the standard deviation of either the sample or deviations from the regression estimates. In the latter case, $CND_i$ is set equal to zero. As before, the subscript i refers to location.
10. Perform simulations for upper river by calling UPRIV.
11. Perform simulations for Truckee Meadows by calling TMEADWS.
12. Perform simulations for lower river by calling LORIV.
13. Print results.
14. Return to step one of this segment to begin calculations for the next constituent.

Subprogram UPRIV calculates mass fluxes and concentrations for inflows to Truckee River above Farad and budgets fluxes and calculates concentrations in this river segment. Sequence of operations in shown in Figure 17. Flows are budgeted in the initial part of UPRIV. Cold Creek flows are estimated from "natural" flows at Farad. "Natural" flows constitute the estimated unregulated flow regimen and were calculated for the hydrologic model by budgeting flows as if storage structures were not present. Estimated flows in Cold Creek and recapitulated dispersed flows in Tahoe-Truckee reach are treated as if actually measured. Errors arising out of this assumption are accounted for in error components of predictive equations for concentrations in Donner Creek and Tahoe-Truckee and Truckee-Farad dispersed flows.

In UPRIV all predictive equations are for concentrations in flows tributary to the mainstem. Simulations are performed sequentially for all months, one station at a time in a downstream direction. The progression of events is similar at all stations. For each flow an initial estimate of the concentration is made for the deterministic part(s) of the predictive equation. Subprogram GAUSS is referenced to obtain a random number from a population of zero mean and unit variance. An error component, calculated as the product of the random number and standard deviation of the residuals, is added to the initial estimate to complete the simulation. For losses in Truckee-Farad reach, dispersed concentrations are set equal to zero.

Procedures at Donner Creek and Prosser and Boca Reservoirs differ slightly from those at other stations. At Donner Creek the random error component is added only after making an initial estimate of concentrations near the confluence with Truckee River. Unexplained variance in predictive equations for Cold Creek and Donner Lake releases is translated downstream and manifested as a single error component.

As discussed in an earlier section, concentrations in reservoir releases are related to concentrations in inflows. Therefore, prior to operation of the predictive equations, lagged inflows are raised to the exponential power peculiar to the exponential relationship between inflows and the constituent under consideration. This procedure economizes on data handling. Concentrations in releases are also dependent on chemical quality in the reservoir during the previous month. The average of observed values corresponding to a particular month which precedes the month during which simulation is initiated are used in reservoir predictive equations. Subsequently, the estimate for a given month is used as a predictor variable for the next month.

Following simulation of concentrations in tributaries and dispersed flows, fluxes are calculated and budgeted through the upper river segment. Although concentrations are estimated at intermediate points along the mainstem, dispersed fluxes are treated as point sources entering the mainstem at Truckee and Farad gaging sites. Concentrations on the mainstem are calculated by dividing mass flux by flow at the point of interest.

Subprogram TMEADWS is used to estimate dispersed fluxes between Farad and Vista and to estimate concentrations in the mainstem at Reno and Vista gaging sites. Figure 18 is a flow diagram showing sequence of operations in TMEADWS. Dispersed flows between Farad and Vista are calculated for all months.

For a given dispersed flow, the deterministic part of the predictive equation is used for the initial estimate of dispersed flux. Subprogram GAUSS is referenced for a random number. The error component (standard deviation of residual fluxes times random number) is added to the deterministic component to complete the flux estimate. This procedure is repeated for all months. Dispersed fluxes are added to fluxes at Farad and concentrations at Vista gage are calculated by dividing total flux by flow past the gage.

Because of the complex hydrology of Truckee Meadows, it was infeasible to simulate mineral concentrations at Reno gage by flux-budgeting methods. Records show that chemical quality of water is often markedly degraded between Reno and Vista gages, primarily because of return flow of poor quality in Steamboat Creek and North Truckee Drain. Therefore, chemical quality at Reno gage is of interest. The deterministic part of the predictive equation is based on concentrations at Farad. Each initial estimate is modified by adding an error component which is determined by referencing GAUSS and multiplying the resultant random number by the standard deviation of the residuals at Reno gage.

Subprogram LORIV calculates mass fluxes and concentrations in the river below Vista gage. Figure 19 is a flow diagram showing sequence of operations in LORIV. Simulations are performed sequentially for all months,

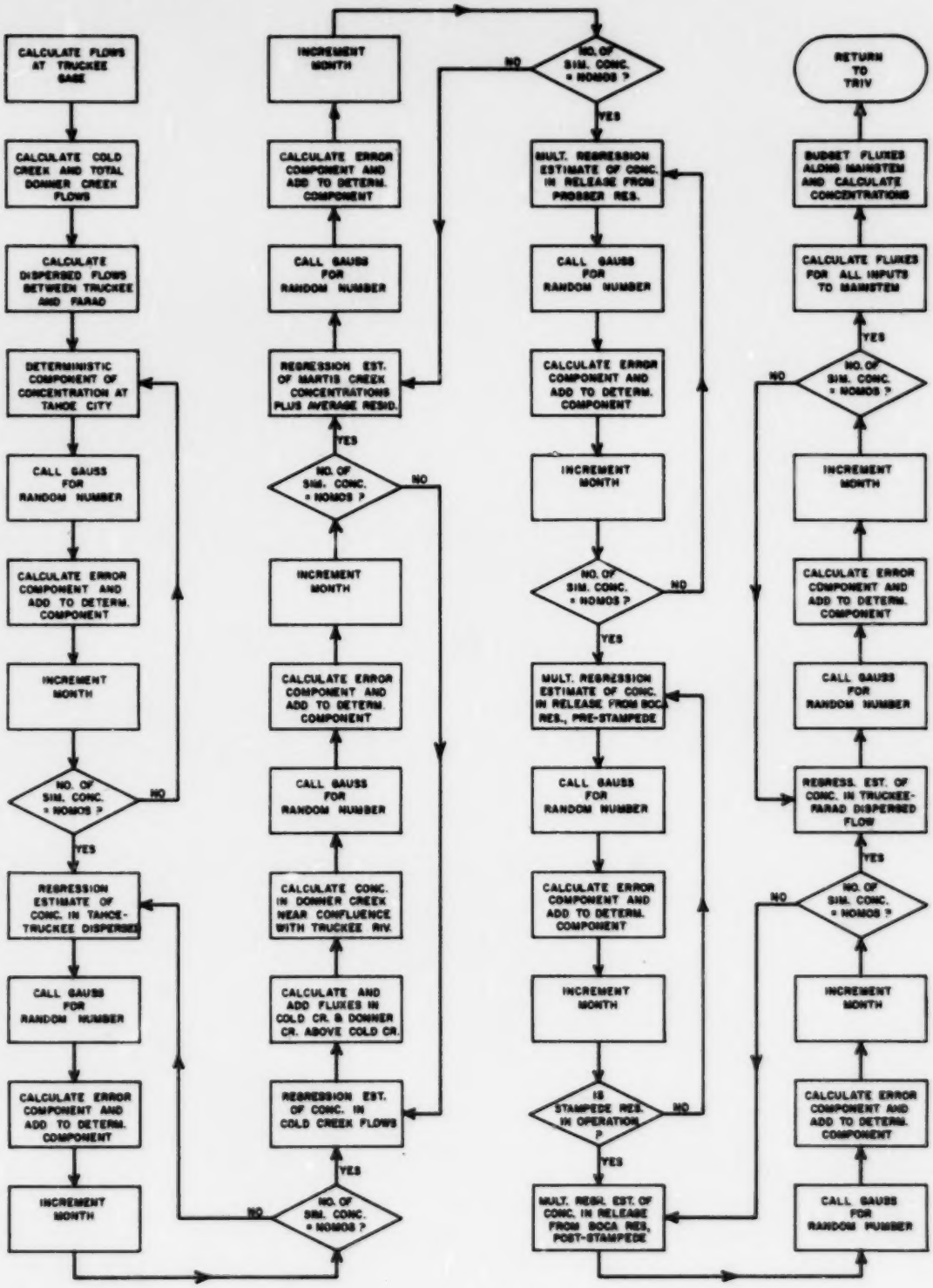
CALCULATE FLOWS AT TRUCKEE GAGE
CALCULATE COLD CREEK AND TOTAL DONNER CREEK FLOWS
CALCULATE DISPERSED FLOWS BETWEEN TRUCKEE AND FARAD
DETERMINISTIC COMPONENT OF CONCENTRATION AT TAHOE CITY
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
REGRESSION ESTIMATE OF CONC. IN TAHOE-TRUCKEE DISPERSED
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
REGRESSION EST. OF CONC. IN COLD CREEK FLOWS
CALCULATE AND ADD FLUXES IN COLD CR. & DONNER CR. ABOVE COLD CR.
CALCULATE CONC. IN DONNER CREEK NEAR CONFLUENCE WITH TRUCKEE RIV.
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
REGRESSION EST. OF MARTIS CREEK CONCENTRATIONS PLUS AVERAGE RESID.
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
MULT. REGRESSION ESTIMATE OF CONC. IN RELEASE FROM PROSSER RES.
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
MULT. REGRESSION ESTIMATE OF CONC. IN RELEASE FROM BOCA RES., PRE-STAMPEDE
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
IS STAMPEDE RES. IN OPERATION ?
NO
YES
MULT. REGR. EST. OF CONC. IN RELEASE FROM BOCA RES. POST-STAMPEDE
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
REGRESS. EST. OF CONC. IN TRUCKEE-FARAD DISPERSED FLOW
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
CALCULATE FLUXES FOR ALL INPUTS TO MAINSTEM
BUDGET FLUXES ALONG MAINSTEM AND CALCULATE CONCENTRATIONS
RETURN TO TRIV

FIGURE 17. Flow Diagram for Subprogram UPRIV.

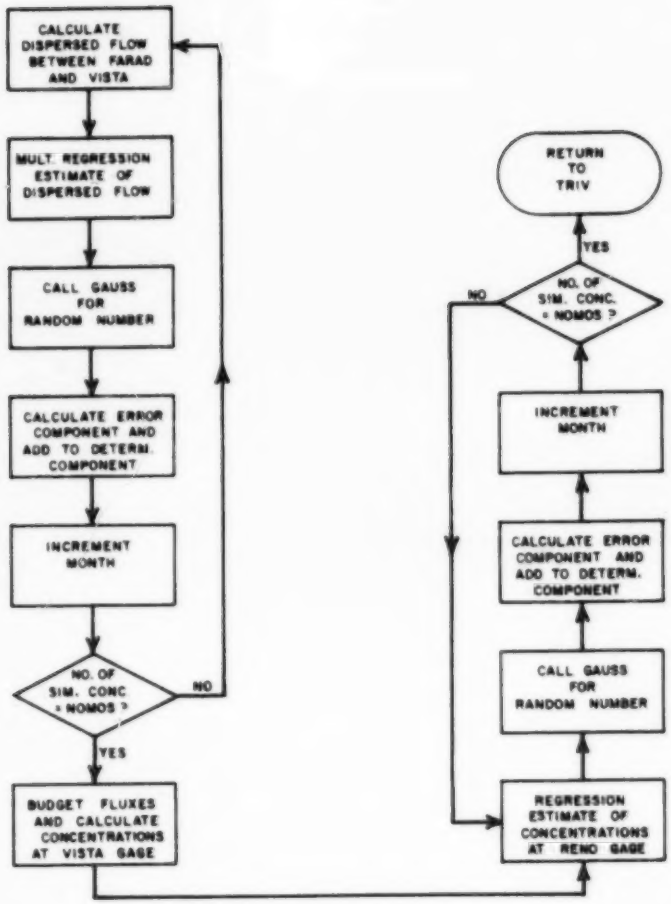
CALCULATE DISPERSED FLOW BETWEEN FARAD AND VISTA
MULT. REGRESSION ESTIMATE OF DISPERSED FLOW
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
BUDGET FLUXES AND CALCULATE CONCENTRATIONS AT VISTA GAGE
REGRESSION ESTIMATE OF CONCENTRATIONS AT RENO GAGE
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
RETURN TO TRIV

FIGURE 18. Flow Diagram for Subprogram TMEADWS.

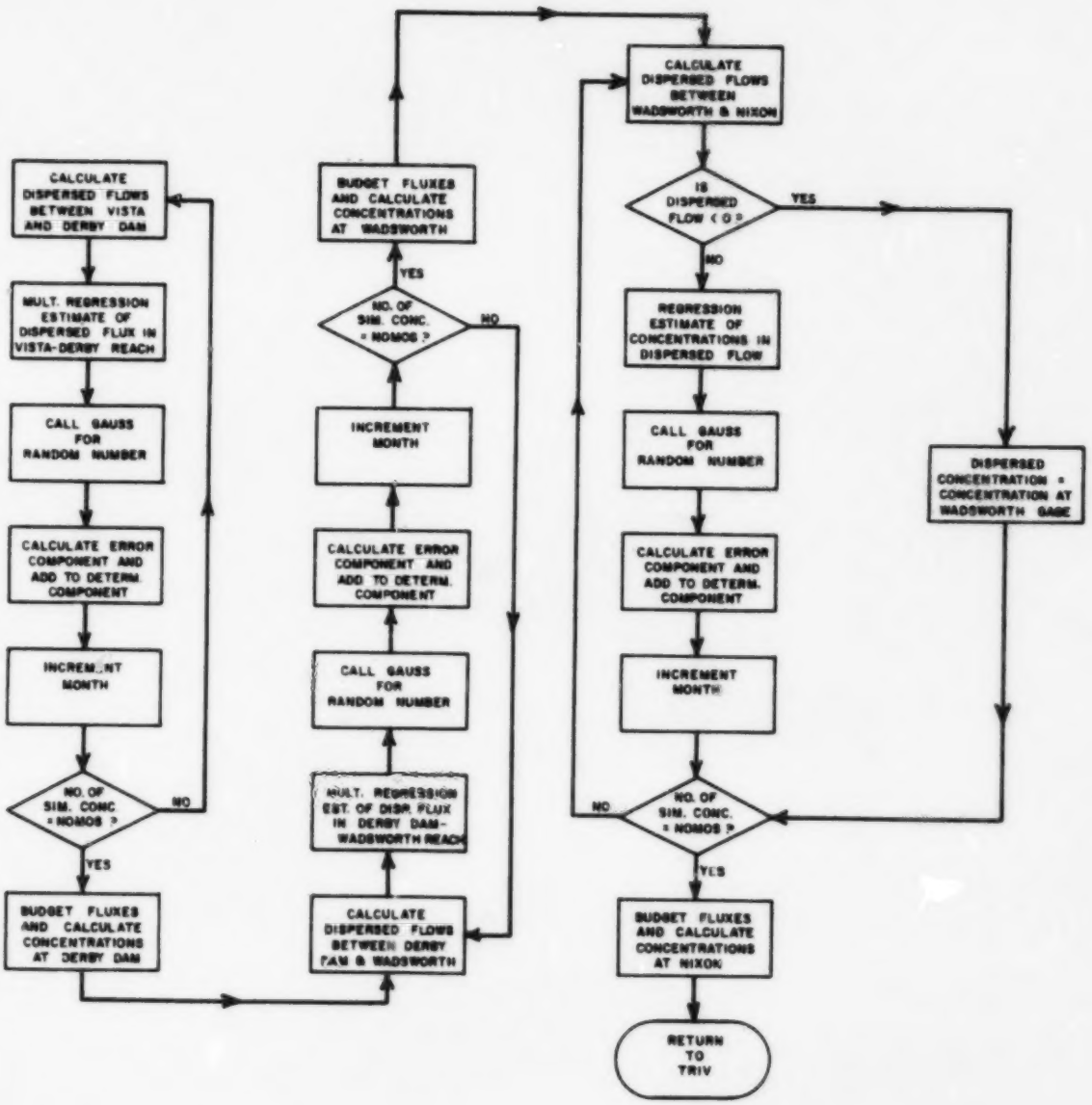
CALCULATE DISPERSED FLOWS BETWEEN VISTA AND DERBY DAM
MULT. REGRESSION ESTIMATE OF DISPERSED FLUX IN VISTA-DERBY REACH
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
BUDGET FLUXES AND CALCULATE CONCENTRATIONS AT DERBY DAM
CALCULATE DISPERSED FLOWS BETWEEN DERBY DAM & WADSWORTH
MULT. REGRESSION EST. OF DISP. FLUX IN DERBY DAM-WADSWORTH REACH
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
YES
NO
BUDGET FLUXES AND CALCULATE CONCENTRATIONS AT WADSWORTH
CALCULATE DISPERSED FLOWS BETWEEN WADSWORTH & NIXON
IS DISPERSED FLOW < 0 ?
YES
NO
REGRESSION ESTIMATE OF CONCENTRATIONS IN DISPERSED FLOW
CALL GAUSS FOR RANDOM NUMBER
CALCULATE ERROR COMPONENT AND ADD TO DETERM. COMPONENT
INCREMENT MONTH
NO. OF SIM. CONC. = NOMOS ?
NO
YES
DISPERSED CONCENTRATION = CONCENTRATION AT WADSWORTH GAGE
BUDGET FLUXES AND CALCULATE CONCENTRATIONS AT NIXON
RETURN TO TRIV

**FIGURE 19. Flow Diagram for Subprogram LORIV.**

reach by reach in a downstream direction. For Vista-Derby Dam reach and Derby Dam-Wadsworth reach, procedures are identical. Dispersed flows are calculated for all months. For each dispersed flow an initial estimate of mass flux is made using the deterministic part of the predictive equation. Subprogram GAUSS is referenced for a random number and an error component is calculated and added to the deterministic component. Estimated fluxes are added to those at the upstream station. Concentrations at downstream stations are calculated by dividing flux by flow. For Vista-Derby Dam reach, flow and flux at the downstream station is based on the sum of that passing Truckee River below Derby Dam and Truckee Canal at Derby Dam gaging sites. For Derby Dam-Wadsworth reach, flux and flow at the upstream end are based only on that passing the gaging site on the mainstem.

Simulation in Wadsworth-Nixon reach is similar to other lower river reaches except that mineral concentrations in dispersed flows are estimated rather than dispersed fluxes. When losses occur in the reach, dispersed concentrations are set equal to concentrations in the mainstem at Wadsworth gage. Dispersed flux is calculated as the product of dispersed concentration and flow. Concentrations at Nixon are derived by dividing total flux by flow.

Subprogram GAUSS was discussed in detail in the section on stochastic component. No further discussion is warranted except to point out that GAUSS is referenced for each predictive equation each time a simulation is made for a component which is additive to the mainstem.

## SECTION VI

## MODEL OPERATION

### INTERNAL VERIFICATION

In simulation, verification is achieved when model output "closely" matches observed data. Definition of the adverb "closely" is subjective and like "beauty", validity is in the eye of the beholder. Although theoretical or statistical criteria may be used to evaluate model output, acceptance or rejection of the model is ultimately based on accuracy with respect to particular objectives and availability and comparative accuracy of alternative methods for achieving the same goals.

Records of chemical quality of water in Tahoe-Truckee system are limited to those developed in the course of this research plus U.S.G.S. data from Truckee River at Floriston, California (near Farad). Data from this project which were used for model verification are from water samples collected monthly from Truckee River at gaging sites near Tahoe City, Truckee, Farad, Vista, Derby Dam, Wadsworth, and Nixon. Number of samples ranged from 48 (November 1967 through March 1972) at upper river sites to 44 (August 1968 through March 1972) at Wadsworth. U.S.G.S. records begin in October 1965 and are from composite samples collected over one month or some fraction thereof. Results are approximately representative of average monthly water-quality conditions. Commencing in October 1969, U.S.G.S. sampling was reduced to one grab sample per month.

Construction of a reliable model from discrete data having a limited length of record was an important objective of this research. In keeping with this constraint, predictive equations were developed from data records of 36 months or less. Initial verification was based on comparisons of model output with observed data from the previously mentioned sites on the mainstem for period December 1967 through March 1972. Data for predictive equations were limited to the period prior to April 1971. Therefore, verification comparisons included observations used to formulate predictive equations plus 12 months of subsequent observations.

Water-quality data collected as part of this research are representative of flow conditions on specific days. Because flows are not monitored at defunct Truckee gage nor in Cold Creek, they must be estimated. Relationships developed for these estimates are based on mean monthly flows. Although it was possible to decompose estimated mean monthly flows in Tahoe-Truckee reach into mean daily flows, it was not possible to do so for Cold Creek flows. As a result, attempts to budget flows on a daily basis resulted in frequent losses from Truckee-Farad reach. Therefore, flow-concentration relations for Cold Creek and Truckee-Farad reach are based on mean monthly flows whereas all others are based on mean daily flows.

Because mean daily flows are often considerably different from mean monthly flows, attempts to budget fluxes on the basis of mean daily flows on days samples were collected were not successful in terms of duplicating observed concentrations on the mainstem at Farad and upstream. To circumvent inconsistencies in flow data and problems arising therefrom, input concentrations were estimated with flow data upon which the flow-concentration relationships were based, but fluxes and flows were budgeted on the basis of mean monthly flows. This method assumes that daily flow conditions along the mainstem above Farad would be proportioned the same as mean monthly flow conditions. As such, the intensive water-quality parameter, concentration, is preserved at each point. In river reaches below Farad it was possible to budget flows and fluxes on a daily basis.

Two procedures were used to test the validity of recapitulated concentrations. To determine if simulation procedures resulted in systematic overestimates or underestimates, arithmetic means of differences between simulated and observed data were compared statistically using procedures from Steel and Torrie (1960) for paired observations. Degree of association (tendency to move in the same direction) between simulated and observed data was determined using correlation coefficients for each constituent at each site. Although these procedures are somewhat redundant, the former is concerned with the null hypothesis that the mean difference between simulated and observed concentrations is not different from zero at some prescribed level of significance. With respect to the latter procedure, the coefficient of determination ($r^2$ = 100 x correlation coefficient squared) at each site can be interpreted as the percentage of variance of the population of observed data explained through the simulation process. If the variance is small, it may be possible to accept the null hypothesis even though simulated and observed values do not vary together. Conversely, simulation may result in a mean difference statistically different from zero even though simulated and observed values are strongly associated. As used in this research, statistics provide a frame of reference for evaluation of the model. Because of probable violations of implicit assumptions in the statistical tests, measures set forth cannot be considered as absolute. They are used only to help locate weaknesses in the

simulation and thereby to promote better understanding of system behavior. Hereafter, the term "accuracy" will refer to the amount of systematic bias in the simulation (relative to Student's t) and to intensity of association (relative to r) between simulated and observed concentrations.

Table 10 shows a statistical comparison of simulated and observed concentrations at each gaging site on the mainstem of Truckee River. Mean and standard deviation of observed concentrations for each constituent are presented as estimated descriptors of the parent population. Mean differences between observed and simulated concentrations show amount of bias in simulation at each site. Statistic "t" is used to determine if mean differences are significantly different from zero. With approximately 50 degrees of freedom (44 to 48), t must be greater than 2.01 to reject the null hypothesis at the five percent level of significance. Correlation coefficients (r) and coefficients of determination ($r^2$) indicate intensity of association between simulated and observed concentrations and percentage of variance explained through the simulation process, respectively. At Tahoe City for those constituents whose simulated concentrations are constant, computation of r and $r^2$ is not applicable.

At Tahoe City the model recapitulates observed concentrations with a high degree of accuracy (without bias) although associative effects tend to be small. As indicated by standard deviations, variances are small and most of it appears to be unexplained. However, a small percentage of that present in $HCO_3$, $SO_4$, Na, K, $SiO_2$ and TDS can be attributed to annual cyclical behavior of those constituents. Similar comments can be made about simulated concentrations at Truckee except that part of the variance is due to dispersed inflows. Correlation coefficients at Truckee for Cl and $SiO_2$ are not significantly different from zero as tested by the Fisher transformation (Roesner and Yevdjevich, 1966). Although the simulation is without bias, variance in Cl and $SO_4$ concentrations is not attributable to dispersed flow-concentration relationships in Tahoe-Truckee reach.

Except for Cl and $SO_4$, accuracy of recapitulation of concentrations at Farad remained at about the level observed at Truckee. The model tends to underestimate Cl concentrations by about 0.5 mg/l and to overestimate $SO_4$ concentrations by about 0.3 mg/l. In practical terms, these biases are insignificant. By present analytical methods 0.5 mg/l Cl and 0.3 mg/l $SO_4$ are near limits or within limits of analytical error for very dilute waters.

Concentrations at Reno are estimated directly from concentrations at Farad. Therefore, each estimate at Reno contains two error components. One is uncertainty in Reno-Farad predictive relationships and the other is uncertainty in predicted concentrations at Farad. However, the level of predictive accuracy demonstrated at Farad appears to be preserved at Reno. Although mean differences between simulated and observed concentrations for Ca and Cl are statistically significant, deviations of 0.3 mg/l and 0.2 mg/l, respectively, are near limits of analytical error for dilute waters.

Figures in Table 10 show that the model tends to over estimate $HCO_3$ Na, K, Ca, $SiO_2$, and TDS concentrations at Vista at the five percent level of significance. Biases are attributable to differences between simulated and observed concentrations for the period April 1971 through March 1972. Although simulations for the final six months are based on preliminary flow data, it is unlikely that errors are sufficient in number or in magnitude to cause the biases. Therefore, the bias may be indicative of changes in the quality regimen of Truckee Meadows. However, as indicated by correlation coefficients, the degree of association between simulated and observed values still improved markedly over that observed at Farad upstream.

Differences between simulated and observed concentrations at Derby Dam are nearly the same as those at Vista as are correlation coefficients. Therefore, bias in simulated $HCO_3$, Na, K, Ca, and TDS concentrations at Derby Dam can be attributed primarily to bias induced at Vista by predictive equations for dispersed fluxes in Truckee Meadows reach.

Predictive equations for dispersed fluxes between Derby Dam and Wadsworth were developed with an inherent negative bias which was caused by adding estimated extremes to each set of observed data. Bias was peculiar to the way data plotted with respect to the estimated extrapolations. Predictive equations for Mg and $SiO_2$ fluxes were not materially affected by this procedure. Although they are not shown in Table 10, differences between simulated and observed concentrations of $HCO_3$, Na, K, Ca, and TDS for the period April 1971 through March 1972 have a disproportionate positive bias with respect to differences for prior months. This bias, like at Derby Dam, is attributable to simulation of dispersed fluxes in Truckee Meadows reach. The degree of association between simulated and observed concentrations is nearly the same as at Derby Dam.

As shown in Table 10, the degree of association between simulated and observed concentrations is greater at Nixon than that at Wadsworth. However, the model tends to underestimate concentrations at Nixon even though negative differences between simulated and observed values are significant at the five percent level only for Cl, $SO_4$, Na, and TDS. The negative tendency is primarily a reflection of underlying negative bias at Wadsworth which has overcome the positive bias originating in Truckee Meadows reach. However, it is also aggravated by the simulation technique in this reach.

## TABLE 10

## STATISTICAL COMPARISON OF SIMULATED AND OBSERVED CONCENTRATIONS AT EACH GAGING SITE ON TRUCKEE RIVER

| | | Est. Population Descriptors | | Test for Bias | | Degree of Association | |
|---|---|---|---|---|---|---|---|
| Gaging Site | Const. | Average Observed Conc. (mg/l) | Stan. Dev. of Obs. Data (mg/l) | Mean Diff. (mg/l) | t | Corr. Coeff. (r) | % Explained Variance ($r^2$) |
| Tahoe City | $HCO_3$ | 51.67 | 1.83 | -0.10 | 0.45 | 0.48 | 0.23 |
| | Cl | 1.80 | 0.28 | -0.06 | 1.47 | --- | --- |
| | $SO_4$ | 2.76 | 0.71 | 0.07 | 0.71 | 0.31 | 0.10 |
| | Na | 6.11 | 0.49 | -0.03 | 0.42 | 0.38 | 0.14 |
| | K | 1.76 | 0.14 | 0.00 | 0.00 | 0.45 | 0.20 |
| | Ca | 8.69 | 0.41 | 0.04 | 0.60 | --- | --- |
| | Mg | 2.41 | 0.16 | 0.02 | 0.80 | --- | --- |
| | $SiO_2$ | 12.78 | 1.32 | 0.14 | 1.03 | 0.69 | 0.48 |
| | TDS | 75.23 | 1.91 | -0.02 | 0.07 | 0.37 | 0.14 |
| Truckee | $HCO_3$ | 48.42 | 5.52 | 0.13 | 0.21 | 0.69 | 0.48 |
| | Cl | 2.23 | 1.14 | -0.23 | 1.40 | 0.18 | 0.03 |
| | $SO_4$ | 3.71 | 1.04 | 0.13 | 0.72 | 0.38 | 0.14 |
| | Na | 5.77 | 1.03 | 0.08 | 0.75 | 0.67 | 0.45 |
| | K | 1.56 | 0.29 | 0.02 | 0.45 | 0.62 | 0.38 |
| | Ca | 8.72 | 0.74 | 0.02 | 0.18 | 0.44 | 0.19 |
| | Mg | 2.42 | 0.24 | 0.03 | 0.59 | 0.45 | 0.20 |
| | $SiO_2$ | 14.33 | 1.85 | 0.34 | 1.12 | 0.18 | 0.03 |
| | TDS | 72.89 | 7.63 | 0.24 | 0.24 | 0.63 | 0.40 |
| Farad | $HCO_3$ | 47.17 | 6.16 | 0.99 | 1.20 | 0.71 | 0.50 |
| | Cl | 2.88 | 1.58 | -0.52 | 2.71 | 0.39 | 0.15 |
| | $SO_4$ | 3.27 | 0.88 | 0.31 | 2.73 | 0.46 | 0.21 |
| | Na | 5.42 | 1.14 | -0.19 | 1.51 | 0.52 | 0.27 |
| | K | 1.44 | 0.26 | 0.05 | 1.53 | 0.64 | 0.41 |
| | Ca | 8.54 | 1.00 | 0.24 | 1.85 | 0.57 | 0.32 |
| | Mg | 2.58 | 0.36 | -0.05 | 0.82 | 0.31 | 0.10 |
| | $SiO_2$ | 16.29 | 1.98 | 0.66 | 1.47 | 0.25 | 0.06 |
| | TDS | 71.45 | 9.36 | -0.92 | 0.86 | 0.63 | 0.40 |
| Reno | $HCO_3$ | 53.20 | 7.53 | 2.73 | 1.59 | 0.58 | 0.34 |
| | Cl | 3.37 | 1.83 | -0.23 | 2.37 | 0.43 | 0.18 |
| | $SO_4$ | 5.40 | 1.63 | 0.07 | 0.32 | 0.29 | 0.08 |
| | Na | 6.16 | 1.41 | -0.12 | 0.67 | 0.45 | 0.20 |
| | K | 1.67 | 0.45 | 0.08 | 1.21 | 0.41 | 0.17 |
| | Ca | 9.86 | 1.27 | 0.34 | 2.10 | 0.53 | 0.28 |
| | Mg | 3.25 | 0.52 | -0.03 | 0.50 | 0.45 | 0.20 |
| | $SiO_2$ | 17.91 | 2.74 | 0.41 | 0.90 | 0.05 | 0.00 |
| | TDS | 83.19 | 12.41 | -0.28 | 0.17 | 0.56 | 0.31 |

TABLE 10 (Continued)

| Gaging Site | Const. | Est. Population Descriptors: Average Observed Conc. (mg/l) | Est. Population Descriptors: Stan. Dev. of Obs. Data (mg/l) | Test for Bias: Mean Diff. (mg/l) | Test for Bias: t | Degree of Association: Corr. Coeff. (r) | Degree of Association: % Explained Variance ($r^2$) |
|---|---|---|---|---|---|---|---|
| Vista | $HCO_3$ | 79.69 | 18.97 | 6.58 | 4.15 | 0.90 | 0.81 |
| | Cl | 9.58 | 3.89 | 0.21 | 0.59 | 0.77 | 0.59 |
| | $SO_4$ | 12.28 | 4.78 | -0.08 | 0.23 | 0.86 | 0.74 |
| | Na | 15.77 | 5.13 | 1.27 | 2.76 | 0.84 | 0.71 |
| | K | 2.90 | 0.79 | 0.27 | 3.45 | 0.83 | 0.69 |
| | Ca | 13.85 | 3.05 | 0.92 | 3.58 | 0.89 | 0.79 |
| | Mg | 4.91 | 1.36 | -0.02 | 0.18 | 0.90 | 0.81 |
| | $SiO_2$ | 21.62 | 8.45 | 1.19 | 1.94 | 0.64 | 0.41 |
| | TDS | 140.96 | 36.69 | 8.00 | 2.76 | 0.89 | 0.79 |
| Derby Dam | $HCO_3$ | 82.86 | 20.89 | 5.78 | 3.79 | 0.92 | 0.85 |
| | Cl | 10.33 | 4.90 | 0.40 | 0.77 | 0.71 | 0.50 |
| | $SO_4$ | 13.29 | 5.37 | 0.42 | 0.96 | 0.83 | 0.69 |
| | Na | 16.73 | 6.04 | 1.55 | 2.73 | 0.81 | 0.66 |
| | K | 3.13 | 0.89 | 0.26 | 3.09 | 0.84 | 0.71 |
| | Ca | 14.52 | 3.50 | 0.75 | 2.58 | 0.90 | 0.81 |
| | Mg | 5.15 | 1.49 | 0.09 | 0.89 | 0.90 | 0.81 |
| | $SiO_2$ | 21.66 | 8.28 | 1 84 | 3.01 | 0.66 | 0.44 |
| | TDS | 148.55 | 41.37 | 8.85 | 2.96 | 0.90 | 0.81 |
| Wadsworth | $HCO_3$ | 99.40 | 36.77 | 3.38 | 1.21 | 0.89 | 0.79 |
| | Cl | 11.54 | 4.88 | -0.71 | 1.63 | 0.81 | 0.66 |
| | $SO_4$ | 21.51 | 13.39 | -2.13 | 2.44 | 0.90 | 0.81 |
| | Na | 20.99 | 8.83 | -0.06 | 0.09 | 0.86 | 0.74 |
| | K | 3.32 | 1.03 | -0.13 | 0.98 | 0.61 | 0.37 |
| | Ca | 17.64 | 6.66 | -0.74 | 1.36 | 0.84 | 0.71 |
| | Mg | 6.55 | 2.81 | 0.13 | 0.63 | 0.89 | 0.79 |
| | $SiO_2$ | 22.06 | 4.09 | 2.53 | 3.16 | 0.61 | 0.37 |
| | TDS | 182.67 | 71.83 | 1.20 | 0.24 | 0.89 | 0.79 |
| Nixon | $HCO_3$ | 107.09 | 42.45 | -2.45 | 1.22 | 0.95 | 0.90 |
| | Cl | 39.59 | 34.58 | -3.54 | 3.24 | 0.98 | 0.96 |
| | $SO_4$ | 40.11 | 32.24 | -2.91 | 2.13 | 0.96 | 0.92 |
| | Na | 35.97 | 24.27 | -3.20 | 3.47 | 0.96 | 0.94 |
| | K | 4.09 | 1.73 | 0.03 | 0.30 | 0.90 | 0.81 |
| | Ca | 24.92 | 13.71 | -1.02 | 1.88 | 0.96 | 0.92 |
| | Mg | 9.47 | 5.75 | -0.20 | 0.99 | 0.97 | 0.94 |
| | $SiO_2$ | 21.04 | 3.41 | 2.96 | 3.27 | 0.43 | 0.18 |
| | TDS | 262.12 | 151.30 | -10.18 | 2.05 | 0.97 | 0.94 |

When losses occur along Wadsworth-Nixon reach, simulated concentrations at Nixon are set equal to those simulated at Wadsworth. Water samples were collected on 10 days during which losses were indicated. Quality data indicate that Truckee River may become more mineralized with respect to $HCO_3$, Cl, $SO_4$ and Na, and consequently TDS, in spite of losses in this reach. Therefore, with respect to available data there is an inherent negative bias in the simulation of these constituents at Nixon.

Accuracy of flow measurements is defined in *Water Resources Data for Nevada, 1971*. If 95 percent of the daily discharges are accurate to within five percent of true values, records are rated "excellent." If they are accurate to within 10 percent, records are rated "good." Flow records at Wadsworth gage are rated "good" and at Nixon gage "excellent." During this research, losses on the 10 days samples were collected averaged 65 percent and ranged from 2.2 percent to 11.5 percent of flows as measured at Wadsworth gage. Because losses were well within measurement error and water quality in the reach was characterized by only 10 pairs of data for conditions of net flow loss, adjustments for apparent bias were judged to be unjustifiable at this time.

To further test validity, the model was checked for internal consistency with respect to simulated concentrations. Results are shown in Table 11. Average concentration of each constituent for the period November 1967 through March 1972 was used in summation of ionic constituents at each site on the mainstem (Table 11, Column 2) and compared to average simulated TDS at each respective site (Table 11, Column 1). Percent differences (Table 11, Column 3) were calculated with respect to simulated TDS. Except at Farad, individual ionic constituents sum to less than simulated TDS. Simulation at Reno appears least reliable and is a reflection of simulation error at Farad plus uncertainties in predictive equations for concentrations at Reno. With possible exception of simulation at Reno, figures in Table 11 show that the model is internally consistent with respect to recapitulated data.

**TABLE 11**

**COMPARISONS OF SIMULATED TDS AND SUM OF INDIVIDUAL SIMULATED CONSTITUENTS**

| Gaging Site | (1) Simulated TDS (mg/l) | (2) Some of Average Simulated Ionic Constituents (mg/l) | (3) Percent Difference With Respect to Simulated TDS |
|---|---|---|---|
| Tahoe City | 75.21 | 73.37 | -2.4 |
| Truckee | 73.13 | 73.01 | -0.2 |
| Farad | 70.53 | 72.13 | 2.3 |
| Reno | 82.91 | 85.75 | -3.4 |
| Vista | 148.96 | 148.13 | -0.6 |
| Derby Dam | 157.40 | 155.26 | -1.4 |
| Wadsworth | 183.87 | 180.69 | -1.7 |
| Nixon | 251.94 | 247.95 | -1.6 |

## EXTERNAL VERIFICATION

For purposes of final verification, the model was operated on the basis of recorded mean monthly flows for the periods October 1973 through March 1972. Recapitulated concentrations at Farad were compared to commensurate U.S.G.S. records (*Water Resources Data for Nevada, 1965-1969*)) at Floriston (2.5 miles upstream from Farad gage) for the period October 1964 through September 1969. TDS was calculated from U.S.G.S. data as sum of individual ionic constituents, less $SiO_2$.

Method of comparison was the same as that used for internal verification. Paired values of simulated and observed data were tested according to procedures in Steel and Torrie (1960). Correlation coefficients were calculated to determine degree of association between observed and simulated concentrations. Table 12 shows comparative statistics for observed and simulated data. Comparisons for $SiO_2$ were not made because of discontinuities in the U.S.G.S. record.

**TABLE 12**

**COMPARISON OF SIMULATED WATER-QUALITY DATA AT FARAD AND U.S.G.S. WATER-QUALITY DATA AT FLORISTON FOR WATER YEARS 1965 THROUGH 1969**

| | $HCO_3$ | Cl | $SO_4$ | Na | K | Ca | Mg | TDS |
|---|---|---|---|---|---|---|---|---|
| Standard deviation, mg/l (simulated) | 6.28 | 0.64 | 1.88 | 0.83 | 0.23 | 1.05 | 0.31 | 9.25 |
| Standard deviation, mg/l (U.S.G.S.) | 7.16 | 0.68 | 1.10 | 1.03 | 0.31 | 1.29 | 0.49 | 10.50 |
| Mean Concentration, mg/l (simulated) | 45.04 | 2.21 | 3.23 | 4.90 | 1.36 | 8.37 | 2.39 | 64.81 |
| Mean Concentration, mg/l (U.S.G.S.) | 45.23 | 1.78 | 3.07 | 4.81 | 1.37 | 8.76 | 2.56 | 68.04 |
| Mean Difference (mg/l) | -0.19 | 0.42 | 0.16 | 0.09 | -0.01 | -0.39 | -0.18 | -3.23 |
| Calculated "t" | 0.31 | 3.47 | 0.57 | 1.03 | 0.01 | 3.34 | 3.62 | 3.13 |
| Correlation Coefficient | 0.76 | 0.24 | 0.17 | 0.74 | 0.61 | 0.72 | 0.65 | 0.71 |

Mean differences between simulated and observed concentrations are significant at the five percent level of significance (t test) in the cases of Cl, Ca, Mg, and TDS. In terms of absolute measure, differences are within or near limits of analytical error. However, comparison of paired simulated/observed concentrations indicate that the model tends to slightly underestimate high extremes. As mentioned earlier, lowest magnitude of annual flows observed in Tahoe-Truckee system during this research was about 78 percent of normal as measured in Truckee River at Farad. Therefore, underestimation of high extremes in concentrations may be because the data base for the model does not reflect drought conditions. Underestimation of high extremes may also be associated with 1) differences in sample points (Farad vs. Floriston) or 2) differences between sampling and water analysis procedures used by the U.S.G.S. and those employed in this research.

Except for $SO_4$, standard deviations of simulated concentrations tend to be slightly less than those of U.S.G.S. data. To determine if variances were equal, they were tested according to procedures in Steel and Torrie (1960) and were found to be statistically equal at the five percent level of significance. Even so, apparent differences in standard deviations may be a reflection of the tendency for the model to underestimate high extremes.

Except in cases of $SO_4$ and Cl, correlations between simulated and U.S.G.S. measured concentrations are as good or better than those of Table 10. In the case of $SO_4$ concentrations, U.S.G.S. values are reported to the nearest 1.0 mg/l whereas simualted values vary in increments of 0.1 mg/l. Because of this difference, simulated concentrations can oscillate within a range of 1.0 mg/l thereby diminishing sensitivity of the statistical comparison. In the case of Cl concentrations, mean and standard deviation are greater for the more recent record (Table 10) than for the older U.S.G.S. record. This plus diminished correlation between simulated and observed U.S.G.S. values may be indicative of relatively recent changes in winter road salting practices.

With existing flow and quality data, the most probable alternative method for simulation of concentrations of dissolved constituents on the mainstem would be to develop flow-concentration relationships at each gaging site. To provide an additional basis for model evaluation, flow-concentration relationships were developed from U.S.G.S. flow data at Farad and quality data at Floriston for water years 1965 through 1969. From graphical analysis, data appeared to conform most closely to the conventional exponential flow-concentration relationship. Least squares regression lines and correlation coefficients were calculated for each set of constituents. Table 13 shows correlation coefficients for flow-concentration relationships and for the flux budgeting method (previously shown in Table 11) to demonstrate the degree of association between observed concentrations and those simulated by the two methods.

With the exception of $SO_4$, correlation coefficients show that flux budgeting accounts for more of the variance in concentrations at Farad than direct estimation from flow-concentration regression equations. Unlike other correlation coefficients in Table 13, those for $SO_4$ are statistically equal at the five percent level of significance. The flux-budgeting method explains more of the variance in the data because it accounts for effects of flow regulation on quality. As effects of regulation diminish and dispersed sources become less well defined in a downstream direction, it is likely that the disparity in predictive ability of the two methods will decrease.

**TABLE 13**

**COMPARISON OF METHOD FOR SIMULATION OF CONCENTRATIONS IN TRUCKEE RIVER NEAR FARAD, CALIFORNIA**

| | Correlation Coefficients for Observed Versus Simulated Concentrations | |
|---|---|---|
| Constituent | Flow-Concentration Method | Flux Budgeting Method |
| $HCO_3$ | -0.57 | 0.76 |
| Cl | -0.03 | 0.24 |
| $SO_4$ | -0.28 | 0.17 |
| Na | -0.50 | 0.74 |
| K | -0.24 | 0.61 |
| Ca | -0.50 | 0.72 |
| Mg | -0.41 | 0.65 |
| TDS | -0.56 | 0.71 |

## FREQUENCY ANALYSES

Public concern over environmental issues in recent years has resulted in promulgation of water-quality standards for rivers and streams throughout the United States. As mentioned in the introductory section, water-qualtiy data are frequently insufficient for description of the water-quality regimen of an entire river system. This is particularly true of Truckee River and other rivers in Nevada. Yet standards have been adopted (as early as July 1957 in Nevada) for a number of locations on interstate waterways and their tributaries. Of necessity, these standards were selected on basis of subjective criteria. Continuing public concern over quality of water resources in the face of expanded scope of human activity and its associated potential for degradation of the resource is forcing re-evaluation of pre-existing standards. It is with regard to this matter that the model has direct application.

Flow frequency analysis is commonly used by engineers for design and evaluation of hydraulic structures and conveyances. The concept involves estimation of the probability of occurrence for flows greater or less than those of a specified size. The anlaysis is usually performed on peak or drought flows selected from equal predetermined intervals over a relatively long period of continuous record. The probability concept provides a basis for assessing risks associated with a given level of design. Within legal constraints, the same concept may be applicable to selection of water-quality standards.

Water-quality data developed in the course of this research are representative of instantaneous flow conditions at times water samples were collected. It is unlikely that data upon which the model is based (36 samples or less for each predictive equation) are representative of either the population of peak concentrations or the population of average monthly concentrations. Through use of the model the sequence of average monthly concentrations in Truckee River and selected tributaries was approximated for period October 1963 through March 1972. The synthetic record is nearly triple the data base used for the model and as such, likelihood of encountering extremes is increased. Synthesized data are representative of the population of concentrations which are likely to be sustained for periods of one month.

The period October 1964 through March 1972 was selected for water-quality simulation because conditions of flow regulation were similar to those under which the model was developed. As indicated by recapitulation of U.S.G.S. water-quality data at Floriston, effects of land development between Tahoe City and Farad on Water quality appear to be minimal during this period. However, there is little doubt that urban development in Truckee Meadows has been reflected by changing water quality in Truckee Meadows reach. Therefore, synthesized data at stations downstream from Farad are undoubtedly biased toward 1968-1971 levels (data base for model) of water quality. Nevertheless, the synthetic record provides a basis from which to examine standards for inorganic chemical quality of water in Truckee River.

TDS, Cl, and $SO_4$ concentrations as reported by the U.S.G.S. for Truckee River at Floriston during water years 1965 through 1969 were subjected to frequency analysis along with simulated concentrations of those constituents at each gaging site on the mainstem. TDS, Cl, and $SO_4$ were chosen because they are the only conservative inorganic constituents of those considered in this research for which standards are commonly set. Theoretical frameworks for distributions of mean monthly concentrations of conservative inorganic chemical constituents have not been developed. Therefore, selection of frequency distributions to be used in the analysis was based on availability of an unpublished computer program developed by Dr. V.L. Gupta, Research Associate and Associate Professor of Civil Engineering, University of Nevada System.

The program fits data to four basic theoretical distributions. Gringorten's (1961) curve numbers one through four are used to test for the basic Gaussian (normal) distribution and three derivatives thereof. Chow's (1954) procedure is used to test for log-normal distributions. Gumbel's (1941) method, Leiblein's (1954) method, and Gringorten's curve number five are used to test for double exponential distributions. Gringorten's curve numbers six and seven are used to test for Fisher-Tippett type II distributions. Selection of the most representative distribution was based on the plotted position of outliers and the statistic

$$R^2 \quad 1 - \frac{\Sigma (W-\hat{W})^2}{\Sigma (W-\bar{W})^2} \qquad \text{(Gupta, 1970)}$$

where

$W$ = observed concentration for a given level of probability,
$\hat{W}$ = theoretical concentration for a given level of probability, and
$\bar{W}$ = mean concentration for the sample.

$R^2$ may vary from 0 to 1. A perfect match between observed and theoretical distributions is achieved when $R^2$ equals 1.

Frequency distributions for U.S.G.S. data at Floriston were compared with those developed from the synthetic record at Farad. Table 14 shows the theoretical frequency distribution, $R^2$, and observed and theoretical events likely to be equalled or exceeded two percent of the time. Theoretical distributions of TDS concentrations are consistent between the two sets of data. However, the theoretical value generated from synthesized data is about 7.5 mg/l less than that from U.S.G.S. data at the two percent probability level. This is consistent with previous analysis (Table 11). Theoretical distributions for Cl concentrations are different but agree within 0.5 mg/l at probability levels of 30 percent or less. Differences occur because the lower bound for Cl concentrations upon which the model is based is higher than that reported by the U.S.G.S. This is also consistent with previous analysis (Table 11). Therefore, in the cases of TDS and Cl concentrations at Farad, it appears that the synthetic record is a reasonable sample of the population of average monthly concentrations.

## TABLE 14

## COMPARISONS OF FREQUENCY DISTRIBUTIONS FOR SIMULATED AND OBSERVED (U.S.G.S.) AVERAGE MONTHLY TDS, Cl, AND $SO_4$ CONCENTRATIONS AT FARAD (FLORISTON)

| | | | Events Equalled or Exceeded 2 Percent of the Time | |
|---|---|---|---|---|
| | Theoretical Distribution | $R^2$ | Obs. Conc. (mg/l) | Theo. Conc. (mg/l) |
| Simulated TDS | Gringorten # 1 | 0.97 | 77.54 | 82.98 |
| U.S.G.S. TDS | Gringorten # 1 | 0.95 | 85.80 | 90.47 |
| Simulated Cl | Gumbel double exp. | 0.99 | 4.00 | 4.16 |
| U.S.G.S. Cl | Log normal | 0.98 | 4.50 | 4.27 |
| Simulated $SO_4$ | Gringorten # 7 | 0.90 | 12.54 | 9.34 |
| U.S.G.S. $SO_4$ | Gringorten # 1 | 0.89 | 5.00 | 5.42 |

The theoretical distribution of simulated $SO_4$ concentrations is considerably different from the theoretical distribution of observed U.S.G.S. values. Differences are caused by outliers in simulated data which are consistent with neither U.S.G.S. data nor those upon which the model is based. The cause for these outliers can be traced to uncertainties in the prediction for $SO_4$ concentrations in dispersed flows along Tahoe-Truckee reach. Effects are identifiable as far downstream as Reno gage. Because $SO_4$ concentrations normally increase by a factor of three to five between Farad and Vista, effects of poor prediction upstream are masked at Vista and points further downstream. Although theoretical distributions for simulated $SO_4$ data are invalid at Truckee, Farad, and Reno, they may be reasonably correct at points downstream from Reno.

With a few exceptions, Gringorten's curve numbers one, two, and three best describe frequency distributions of recapitulated (simulated) Cl, $SO_4$, and TDS data at stations upstream from Nixon. Gringorten's curve number six best describes the distribution of Cl concentrations at Truckee. At Wadsworth, Gumbel's method resulted in the best fit for $SO_4$ data. All three constituents at Nixon were best represented by the double exponential distribution as described by Gringorten's curve number five Figures showing cumulative frequency distributions and plotted Cl, $SO_4$ (except at Truckee, Farad and Reno), and TDS for each site are contained in Appendix C of Volume II of this report.

It is interesting to compare published standards ("Water Pollution Control Regulations," State of Nevada Division of Health, Bureau of Environmental Health, 1967) for Cl and total dissolbed solids with frequency distributions developed for those constituents. Although the method for determining total dissolved solids is not specified in the regulations, it is assumed to be residue on evaporation. To make the standard commensurate with TDS as defined for this research, it was necessary to apply a correction factor. Residue on evaporation is nearly equivalent to the dissolved $HCO_3$ concentration divided by 2.03 plus the sum of the concentrations of remaining dissolved constituents (Hem, 1970). To make the standard equivalent to the sum of dissolved constituents less $SiO_2$ (TDS), one-half the average observed $HCO_3$ concentration was added and the mean observed $SiO_2$ concentration was subtracted for each station.

Standards used for comparisons are those listed as limits for the annual average concentration. Except for Lagomarsino Bridge, control points for standards are near gaging stations. Although Lagomarsino Bridge is about three miles from Vista gage, analysis of water samples from both sites show that TDS concentrations are nearly the same. Results of comparisons (control versus simulation point) are shown in Table 15. Figures in Table 15 show that average monthly TDS concentrations which are numerically equivalent to the adjusted standard have low probabilities for recurrence. Therefore, the standard as an average annual concentration will be equalled or exceeded even less frequently. Farad was the only station for which an annual average Cl concentration was specified. An average monthly Cl concentration of 4 mg/1 (standard is 4 mg/1 as annual average) would be equalled or exceeded only two percent of the time at Farad. It is unlikely that the standard has been violated.

From the above comparisons, it is clear that frequency distributions provide a basis from which standards may be quantitatively evaluated. When economic or legal constraints (such as a "nondegradation" policy) are involved, it is especially important to understand ramifications of setting standards at a particular level. Because water-quality data are seldom adequate for identification of frequency distributions, the modeling approach for extrapolation of the data base appears feasible.

## TABLE 15

## PROBABILITIES OF RECURRENCE OF AVERAGE MONTHLY TDS CONCENTRATIONS WHICH ARE NUMERICALLY EQUAL TO STANDARDS FOR MAXIMUM ALLOWABLE ANNUAL CONCENTRATIONS OF TOTAL DISSOLVED SOLIDS

| Control Point | Model Simulation Point | Published Avg. Annual Standard (mg/l) | Adj. Pub. Std. (mg/l) | Prob. of Recurrence of Avg. Mo. TDS ≥ Std. |
|---|---|---|---|---|
| Farad | Farad gage | 80 | 87 | 1% |
| Boynton Lane | Reno gage | 125 | 133 | <<1% |
| Lagomarsino Bridge | Vista gage | 150 | 168 | 33% |
| Ceresola Ranch | Wadsworth gage | 250 | 277 | 10% |

## SECTION VII

## REFERENCES


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## SECTION VIII

## GLOSSARY

**Conservative behavior** - Changes in dissolved load are associated only with accretions or depletions in streamflow.

**Energy grade line** - A plot to total available energy versus distance in the direction of flow.

**Evapotranspiration** - The transfer of water from liquid to vapor state through the combined processes of transpiration by plants and evaporation.

**Grab sample** - A water sample collected at a single point in a stream within a short period of time (usually 2-5 minutes).

**Hydraulic control** - Any structure, artificial or natural, or break in channel slope which causes flow velocity to transition from subcritical to supercritical regime (or vice versa).

**Hydraulic exponent** - An exponent used for graphical determination of depth of either uniform or critical flow in channel cross sections of a specified geometry.

**Mass flux** - The mass rate of flow of dissolved constituents (M/T).

**Uniform flow** - For the time period under consideration, depth of flow in the reach is everywhere the same (same as steady uniform flow).

**Variance** - A statistical measure of dispersion or scatter about the mean (also known as mean square). It is **defined** as sum of squares of deviations from the mean divided by one less than the total number of observations.